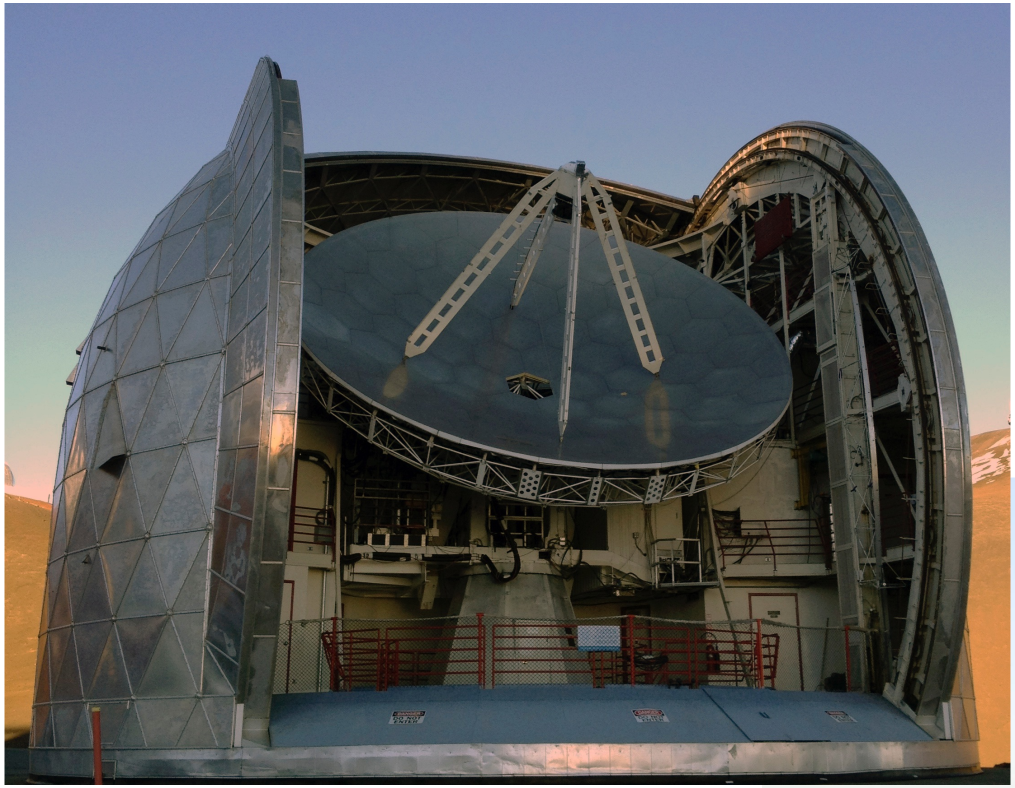
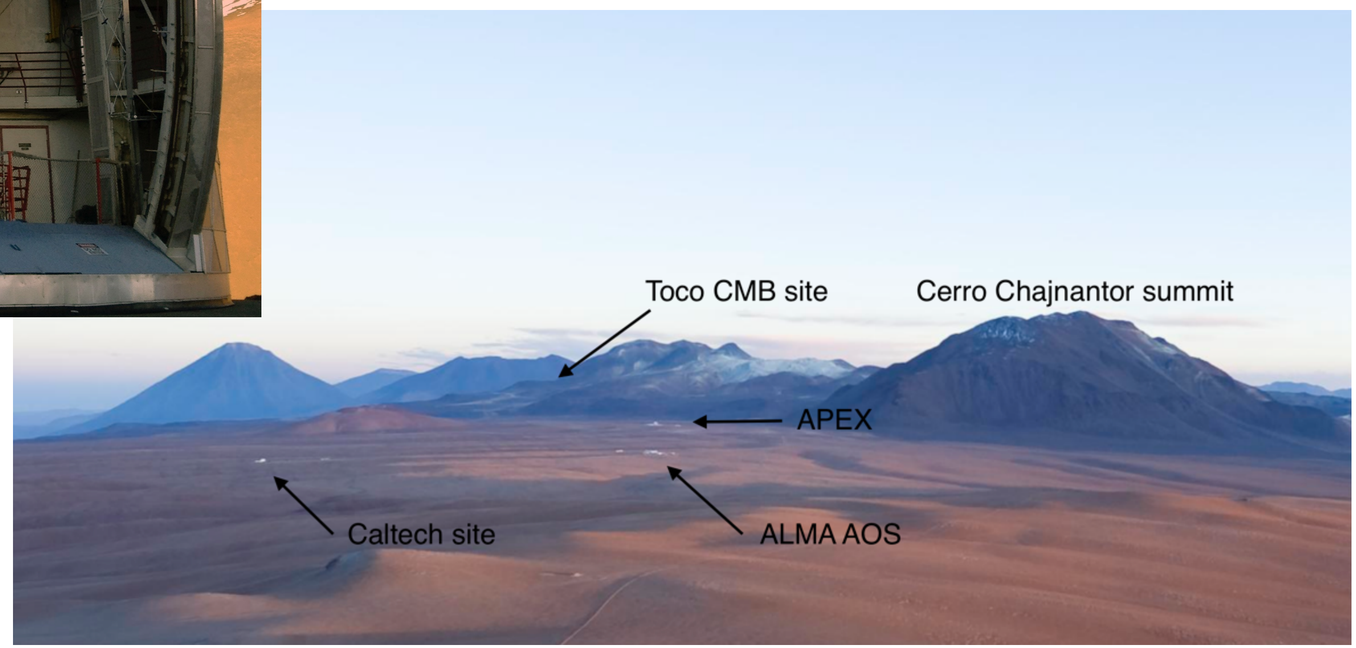
The Leighton Chajnantor Telescope



UNIVERSIDAD DE CONCEPCION



S. Golwala

IRSIG Telecon

2019/01/15

Overview

Summary

CSO history

LCT Concept, Science Opportunities, and Status

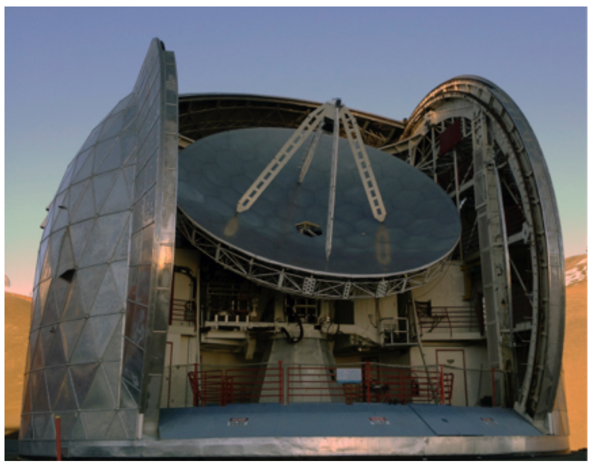
including ideas for community participation

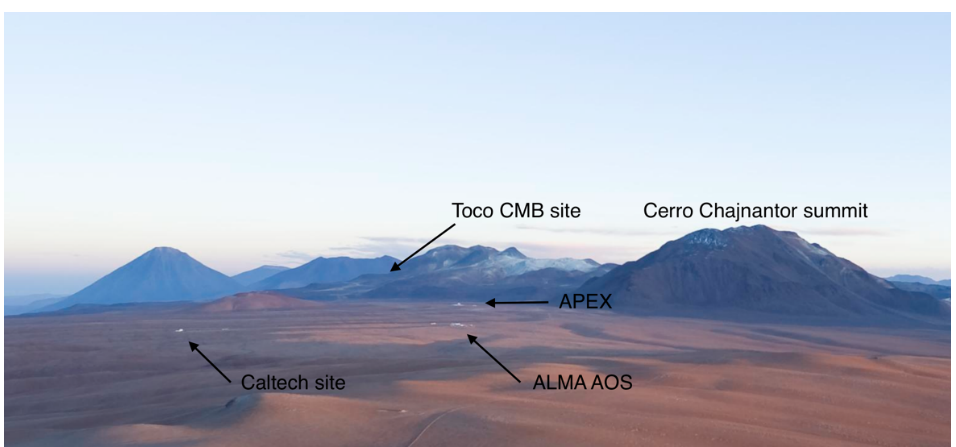
LCT Summary

UNIVERSIDAD DE CONCEPCION

Conceptual Design Report
for the
Leighton Chajnantor Telescope

November 2, 2016



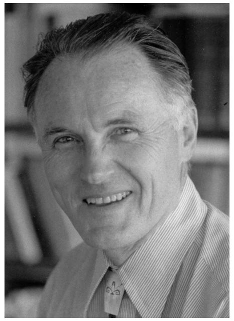


- Move 10.4-m, 11 μm rms Leighton Telescope to CBI site inside ALMA
- New, simple enclosure
- Observing Program
  - Large (1000-hr) projects not otherwise possible, using cutting-edge instrumentation
  - Technology demonstrations
  - Continued access for PI nights
- Fully remote operations
- Chilean and Chinese institutions to take lead on operations
  - Shanghai Normal University Key Lab for Astrophysics: C. Shu
    - Chilean work managed by CAS South American Center for Astronomy (CASSACA): Z. Wang (also SAO)
  - U de Concepcion Center for Astronomical Instrumentation (CePIA): R. Reeves

CSO History and Status

CSO History

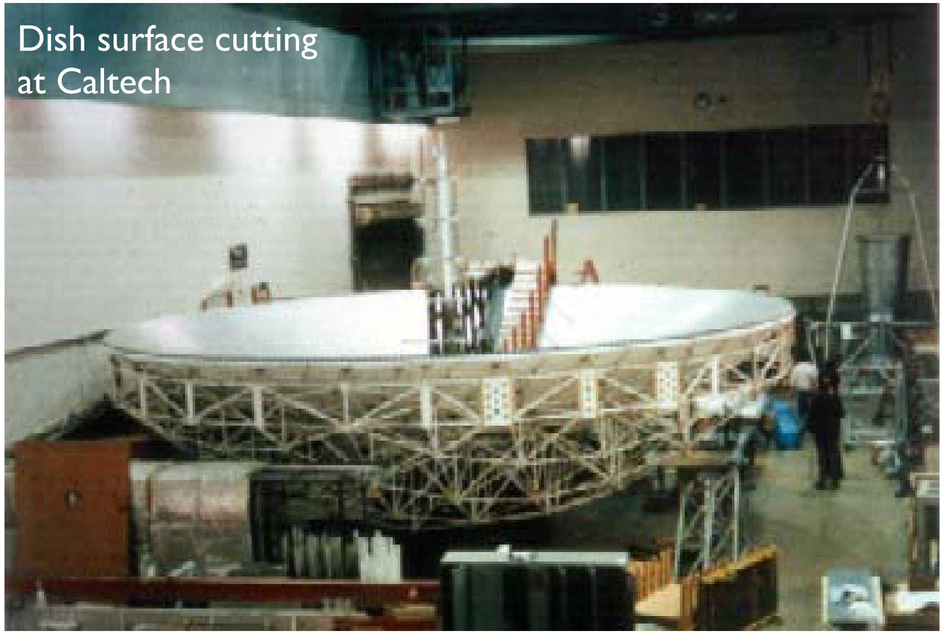
Bob Leighton



Tom Phillips

Grew out of an effort by Leighton in the 1970s to open up the study of the molecular ISM

- w/ Neugebauer and Moffat, proposed to NSF 3-element interferometer in Owens Valley + single-dish for high, dry site
- Developed a technique for inexpensive construction of 10-m segmented, parabolic, homologous dishes capable of submm surface accuracy (1975-1980)
  - Funded by NSF, NASA, and Kresge Fdn
  - Constructed the Caltech High Bay, where the Palomar mirror was polished, w/Caltech undergrads!



Dish surface cutting at Caltech

- Brought Tom Phillips from Bell Labs, where he had developed the SIS tunnel junction mixer (1970s) and embarked upon mm/submm astronomy, to Caltech as director-designate
- NSF delayed start of CSO until completion of OVRO interferometer, funded CSO construction in 1984; first light 1987.

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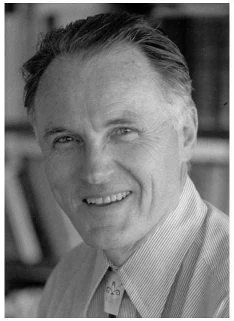

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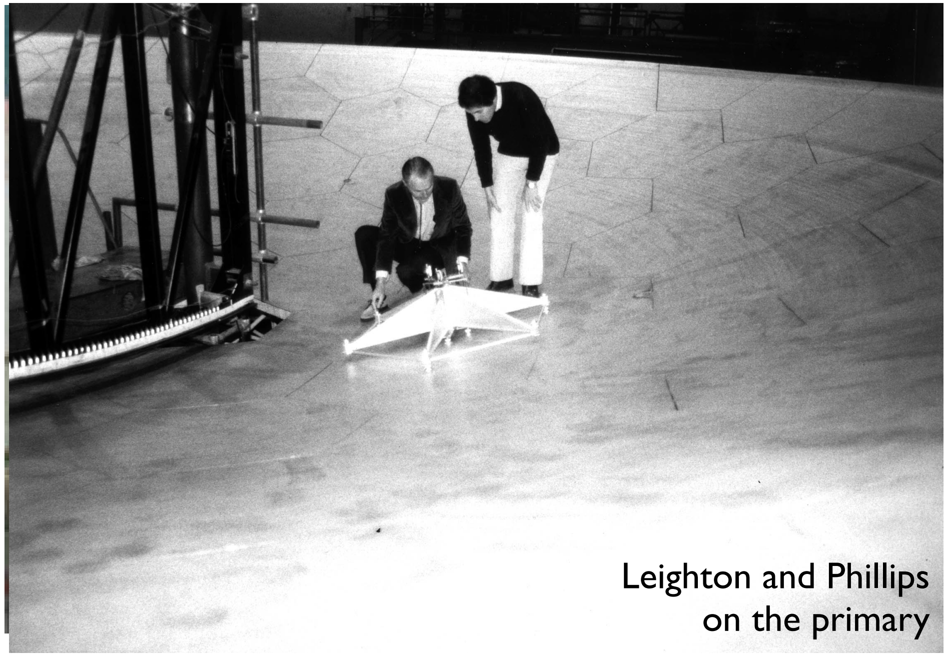

Leighton and Phillips on the primary

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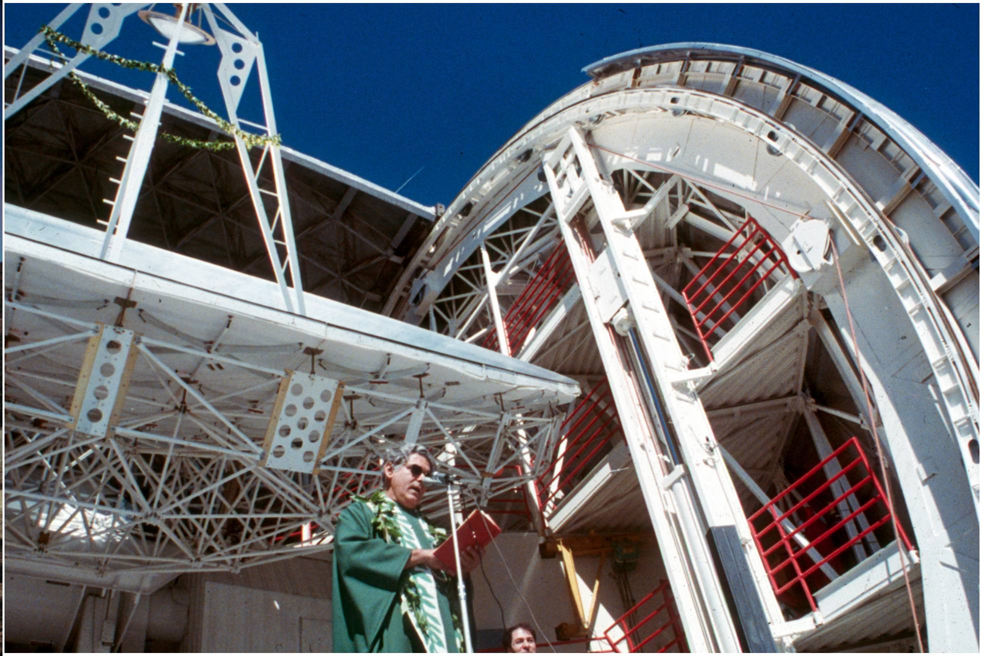
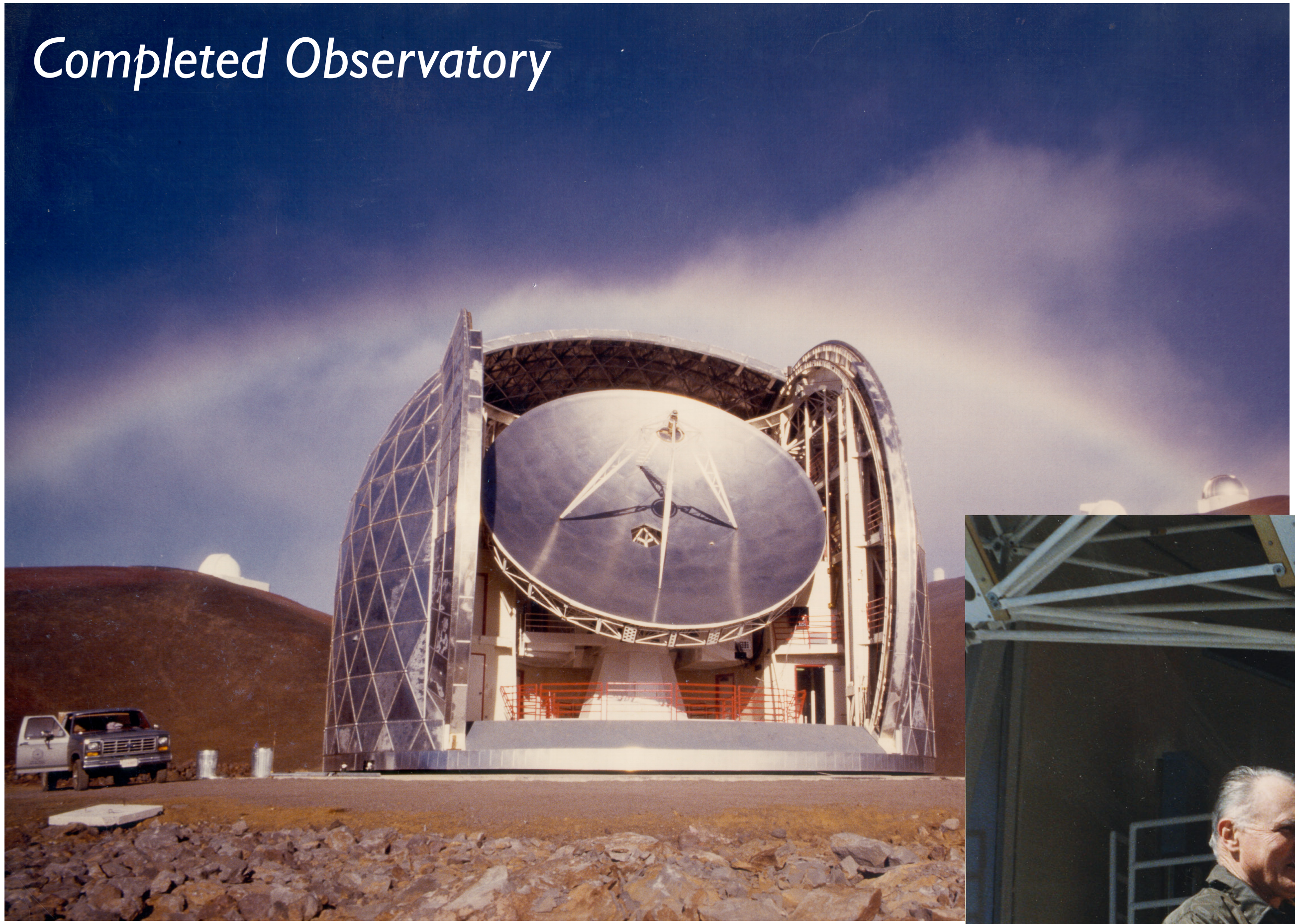
CSO Construction



CSO Construction

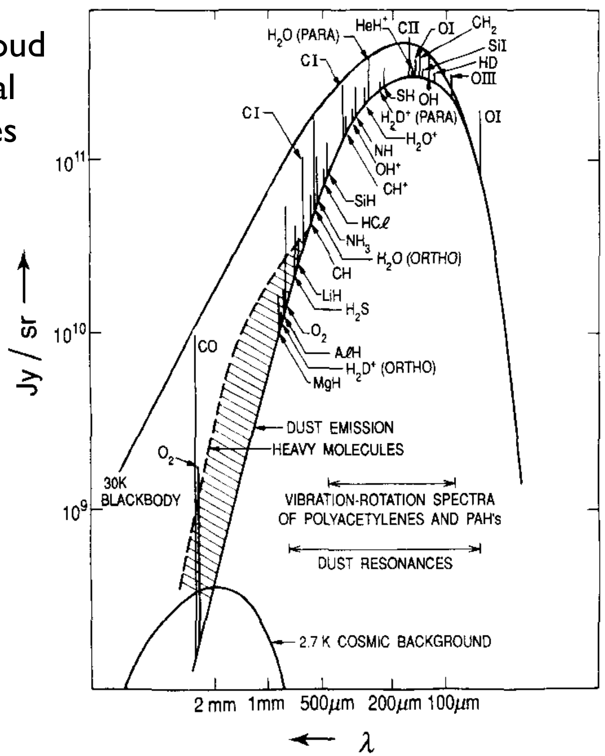


CSO History

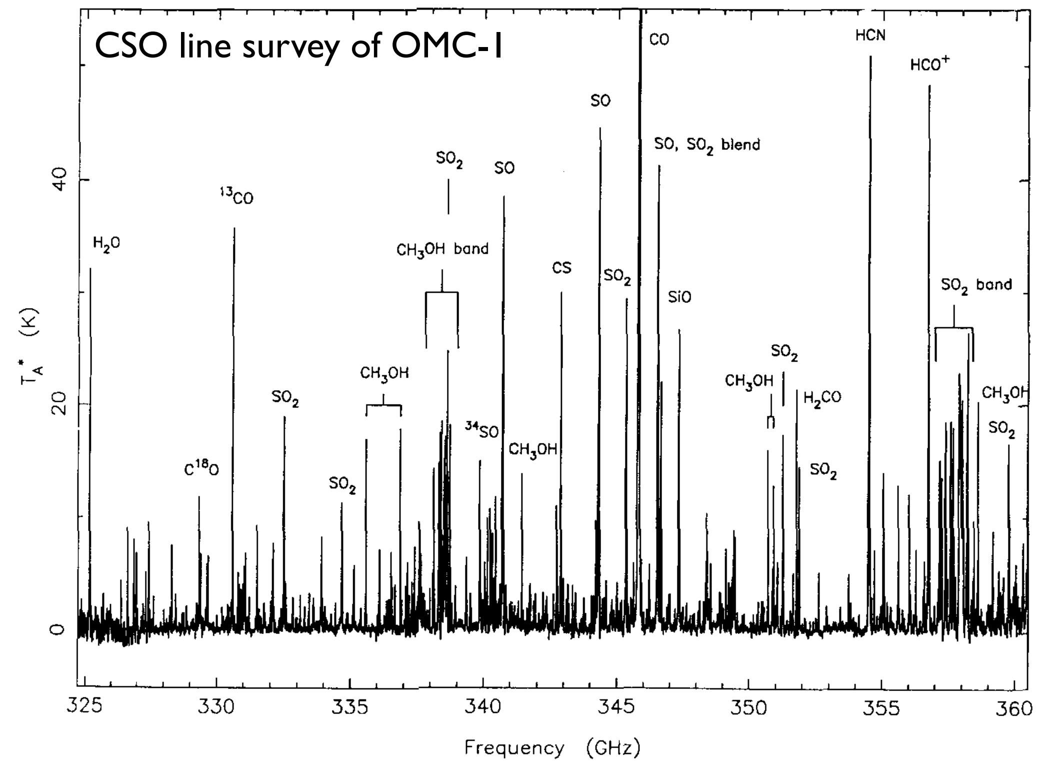
1990s: Primarily heterodyne instrumentation, first submm local ISM line surveys, searches in nearby galaxies, omnipresence of [CI], turbulence in ISM, studies of atmosphere in submm

Line surveys: Groesbeck+ (1992), Schilke+, Comito+

ISM cloud spectral features



Phillips and Keene (1992)



Groesbeck, Blake, and Phillips (1992)

CSO History

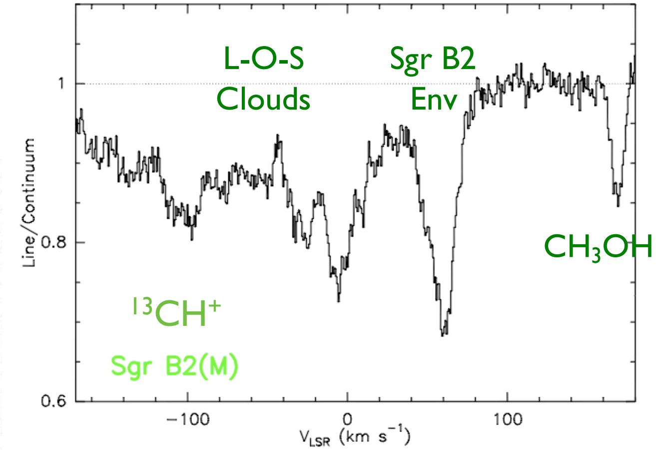
2000s: First large continuum arrays, continued heterodyne work

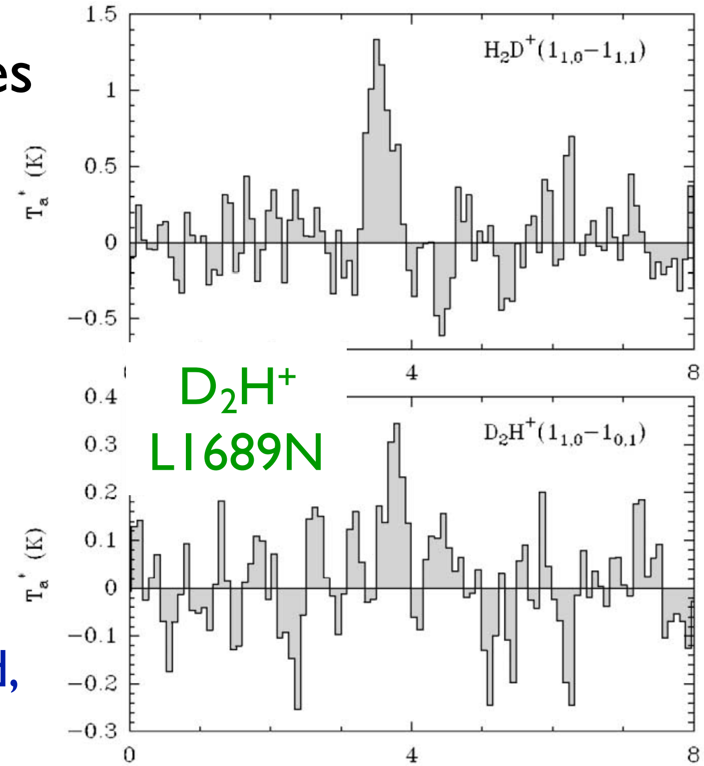
- Dev't of remotely operable, tunerless wide-bandwidth balanced heterodyne receivers
- SHARC II: 350 μm imaging and polarimetry
  - Important SED point for dusty, star-forming galaxies (DSFGs) from submm surveys
  - Dusty sources in our galaxy
  - High resolution imaging of debris disks
  - Polarimetry with SHARP optics module
- Bolocam: 1 mm/2 mm imaging
  - Extragalactic continuum surveys for DSFGs
  - 220 deg^2 of the galactic plane to 15-30 mJy rms; longitude -10 to 54°, latitude ±0.5°
  - 1' resolution SZ imaging out to R_{500} to R_{vir}
- Z-Spec: direct detection spectroscopy across the 1 mm window
  - CO ladder, H_2O, other molecular lines
  - High-z [CII]
  - Modeling of radiation environment in ISM
- ZEUS: direct detection spectroscopy in 350 μm, 450 μm, 600 μm windows
  - [CII] and other atomic species at moderate redshift (z ~ 1-2)
  - Modeling of radiation environment in ISM

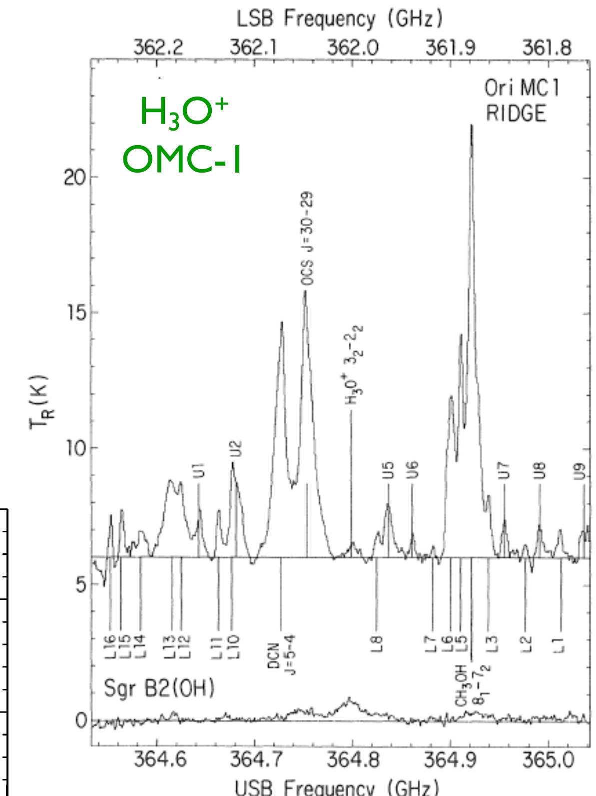
CSO History: Hydride Spectroscopy

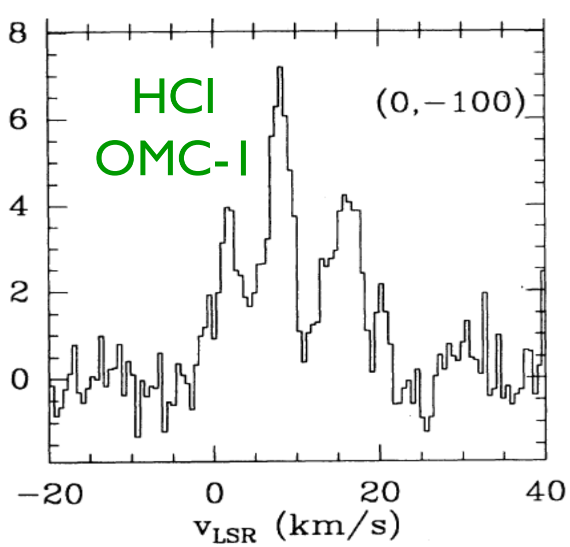
Spectroscopy of hydrides

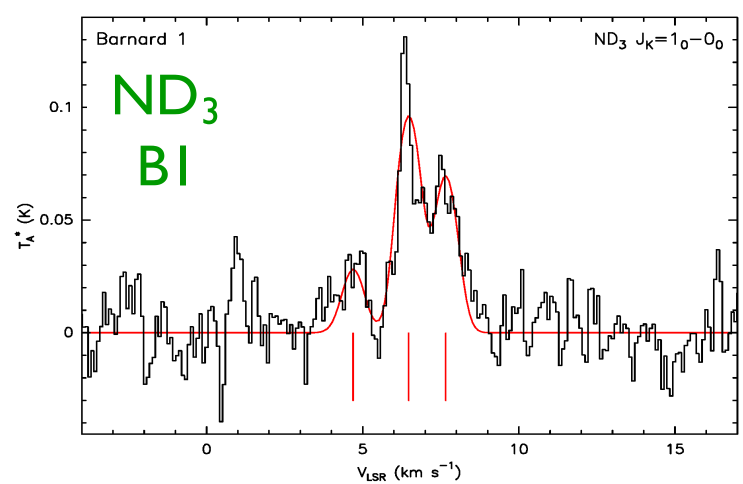
- H_3O^+ (Phillips+)
- HCl (Schilke+)
- D_2H^+ (Vastel+)
- ND_3 (Lis+)
- $^{13}CH^+$ (Falgarone+)
- CH_2D^+ (Roueff+)
- Importance of deuterium fractionation in the cold, dense ISM







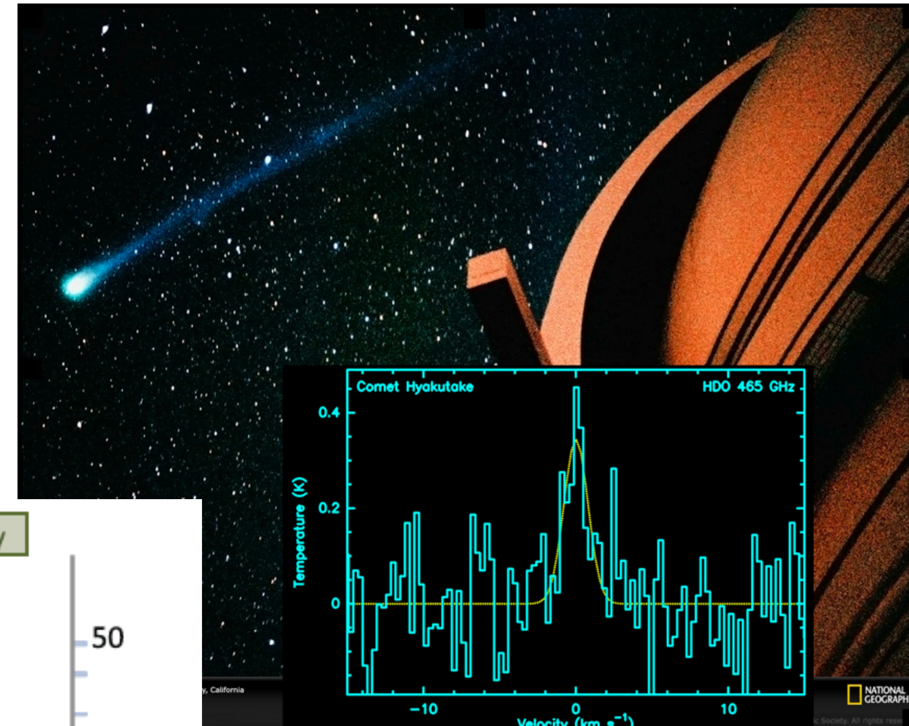


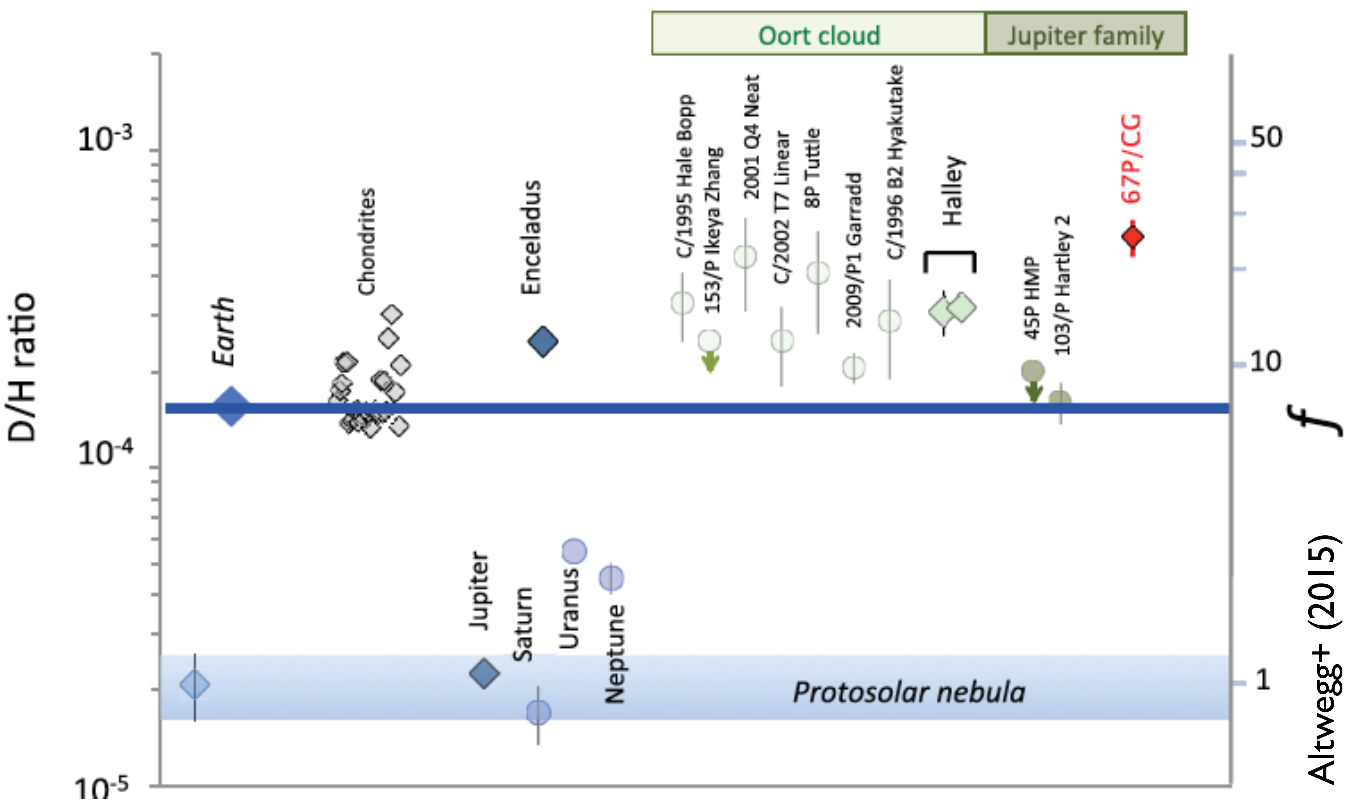


CSO History: Comets

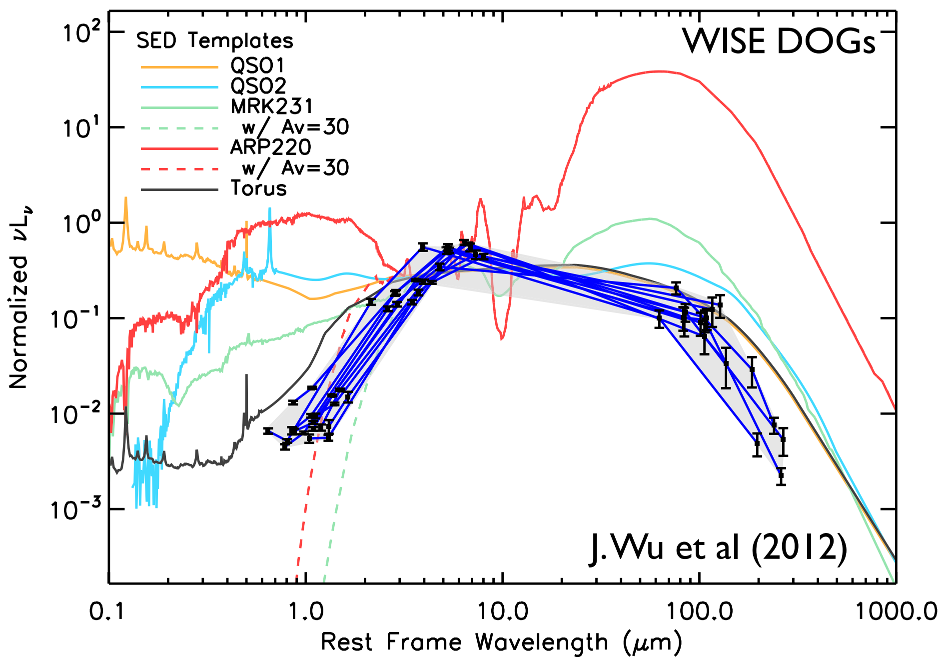
Spectroscopy of comets

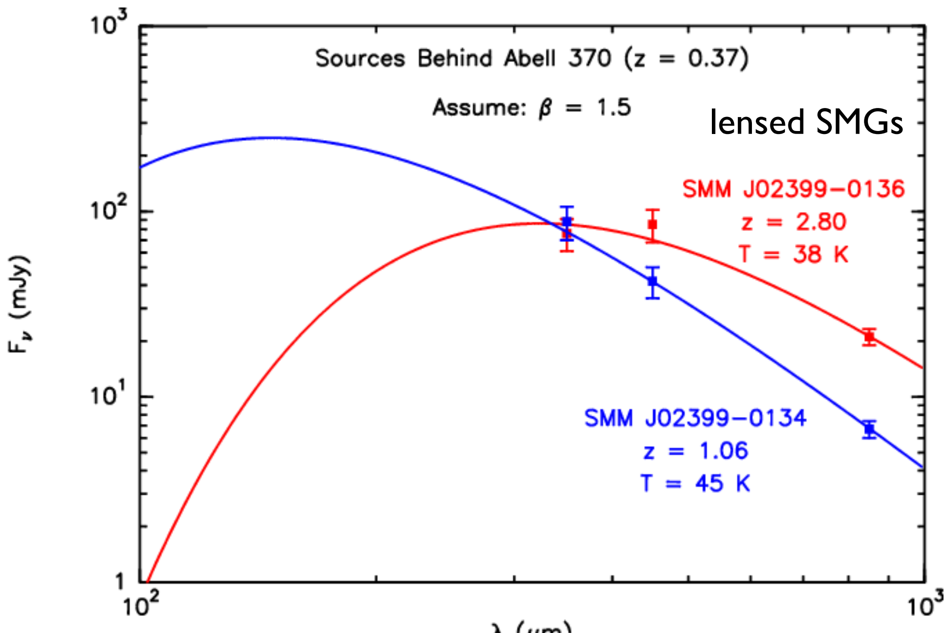
- Detections of many new cometary volatiles
- First ground-based detection of HDO in comet Hyakutake: origins of Earth's water?





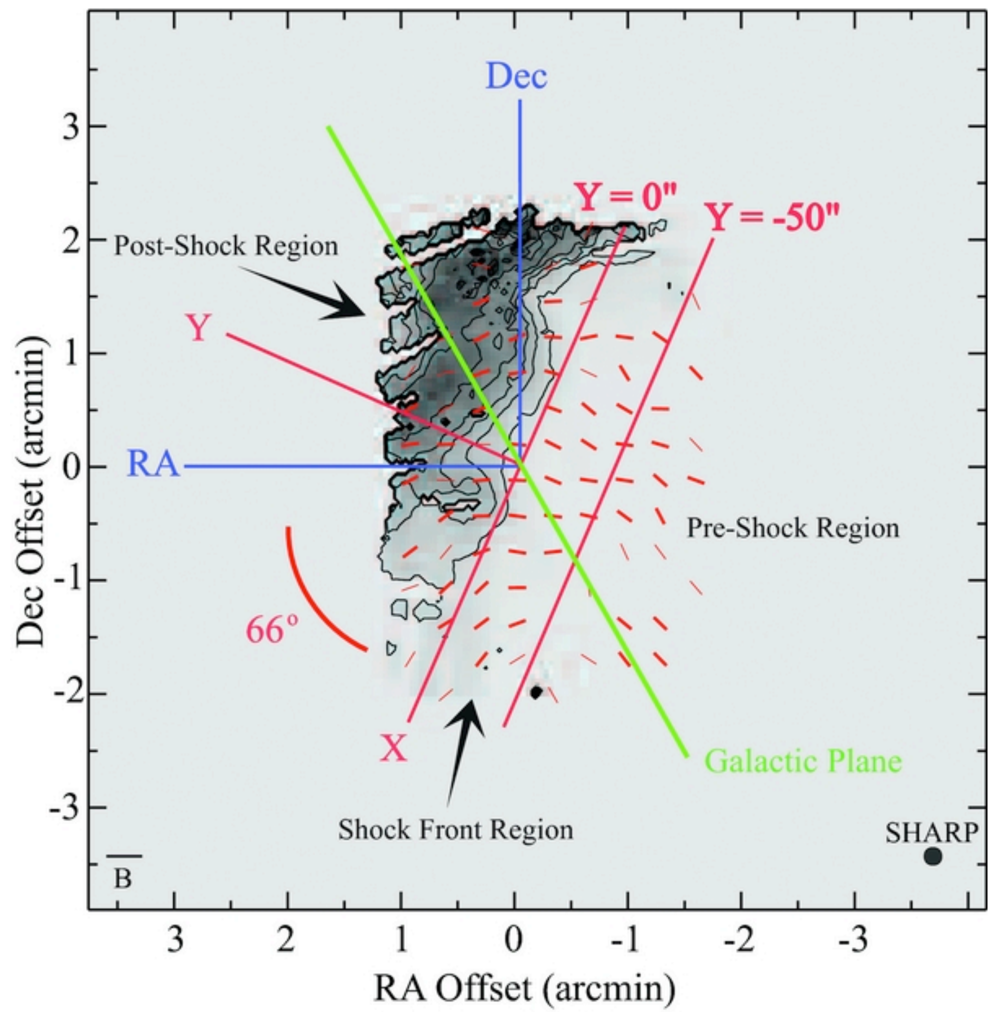
CSO History: SHARC II 350 μm Imaging/Polarimetry





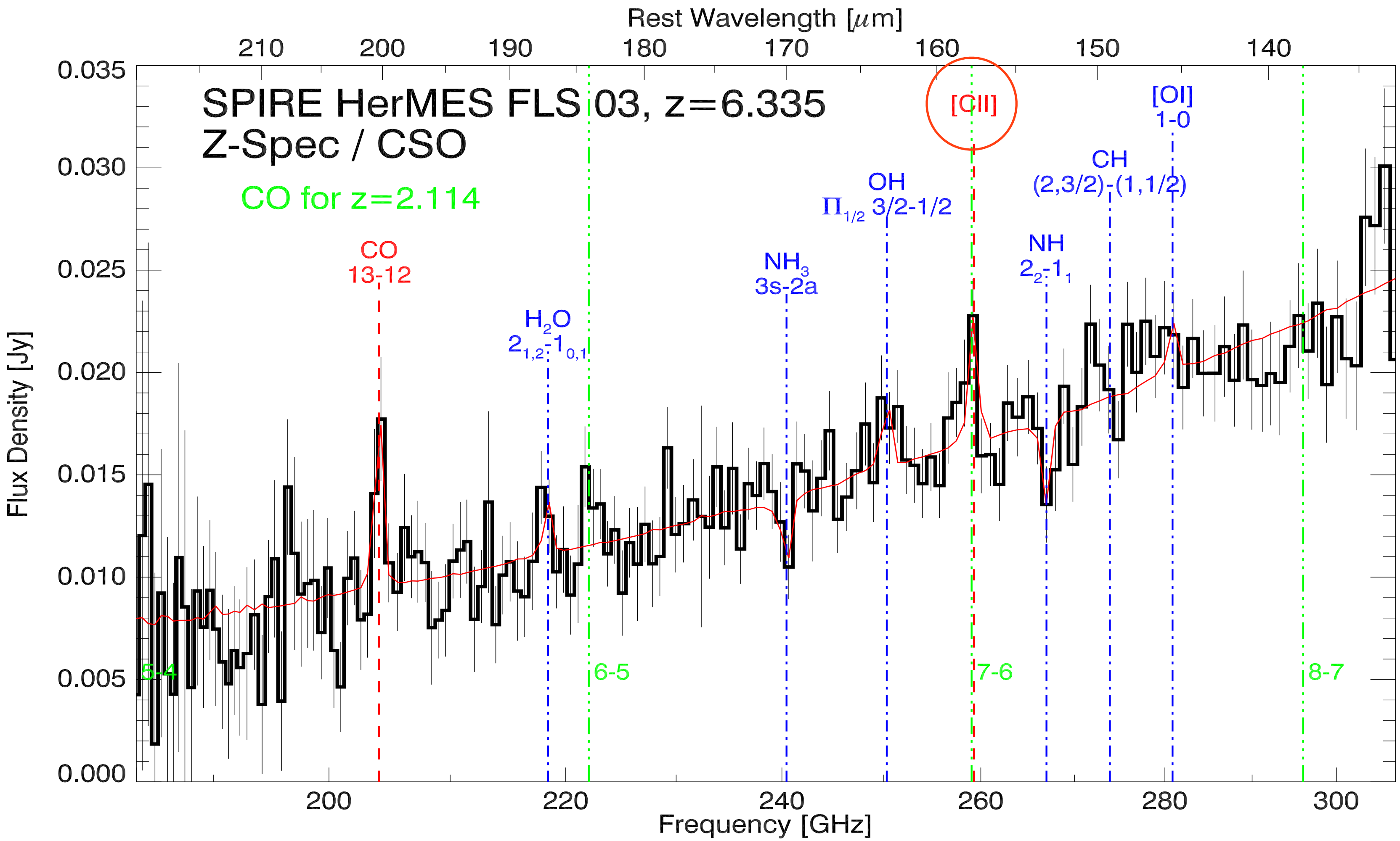
SHARCII provides crucial 350 μm SED point

Vaillancourt et al (2013):
SHARP measurements elucidate shock front created by stellar winds from OB stars



CSO History: The ISM in High-Redshift Galaxies

Toward the future: a *Herschel*/SPIRE source at z = 6.3

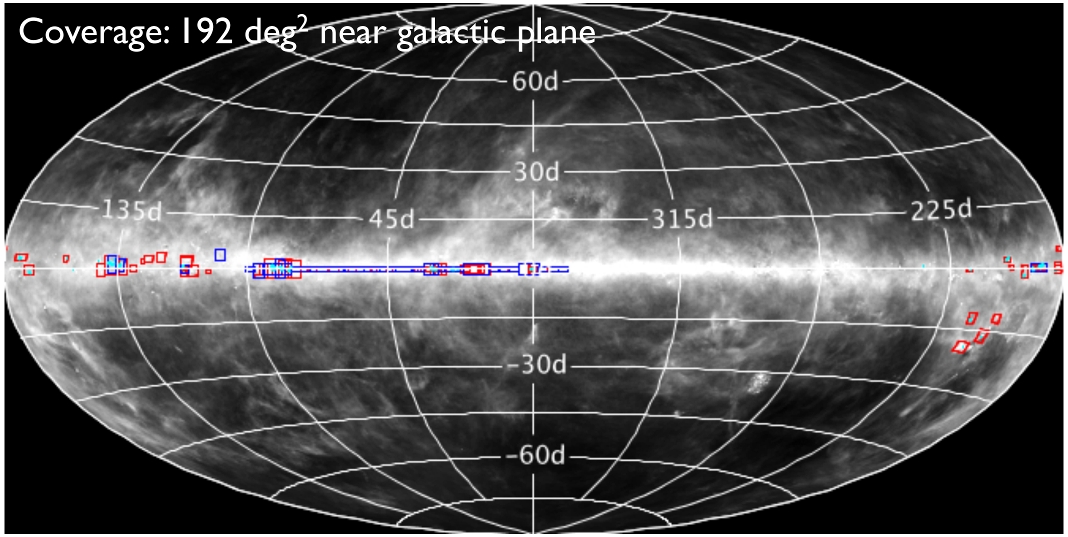


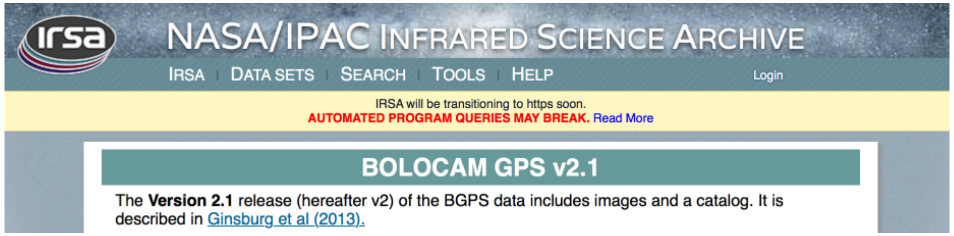
One of the long-wavelength (500 μm) peakers in SPIRE

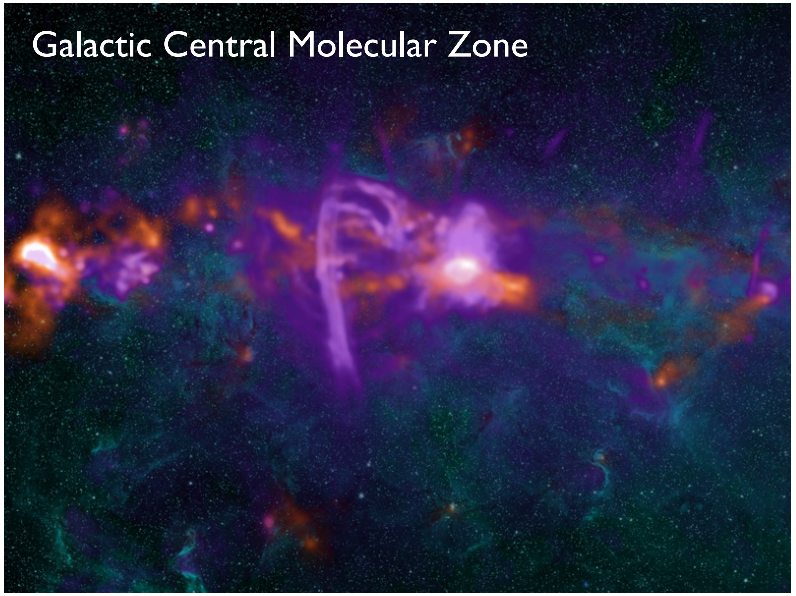
Redshift discovered with CARMA, confirmed with Z-Spec, including [CII]

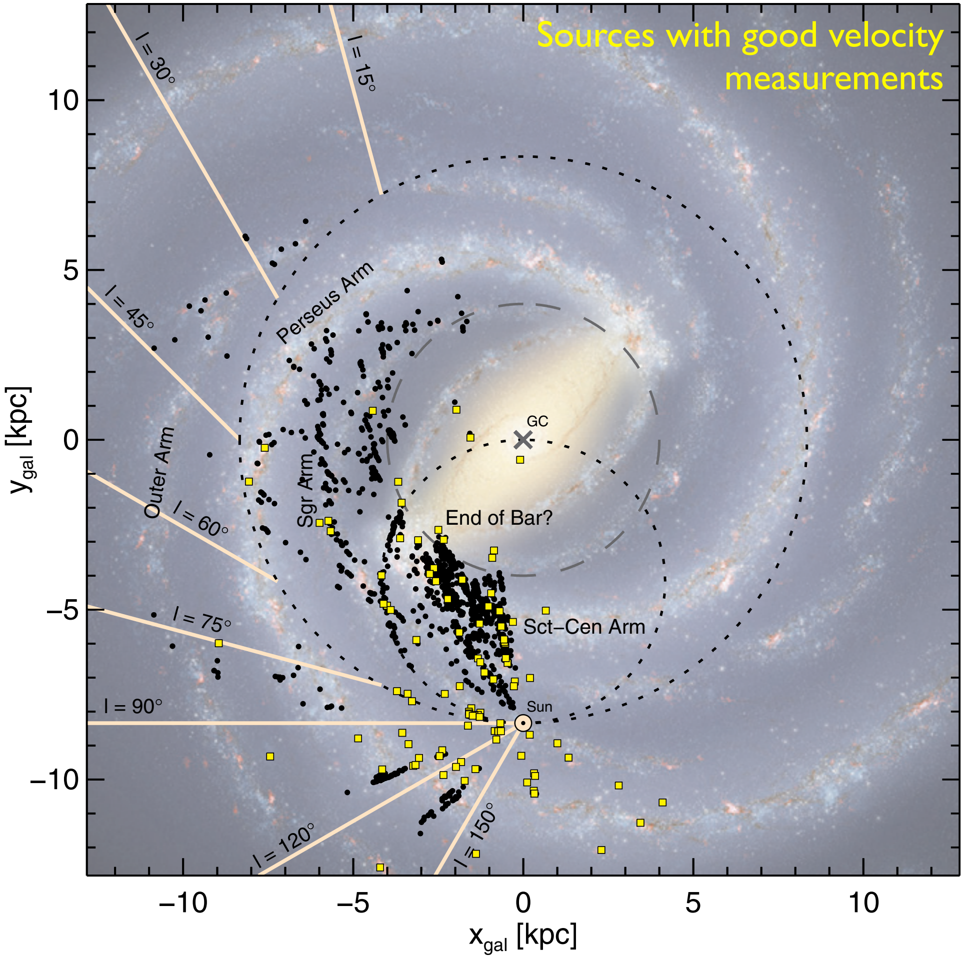
CSO History: Unbiased Surveys of the Galaxy

Bolocam Galactic Plane Survey

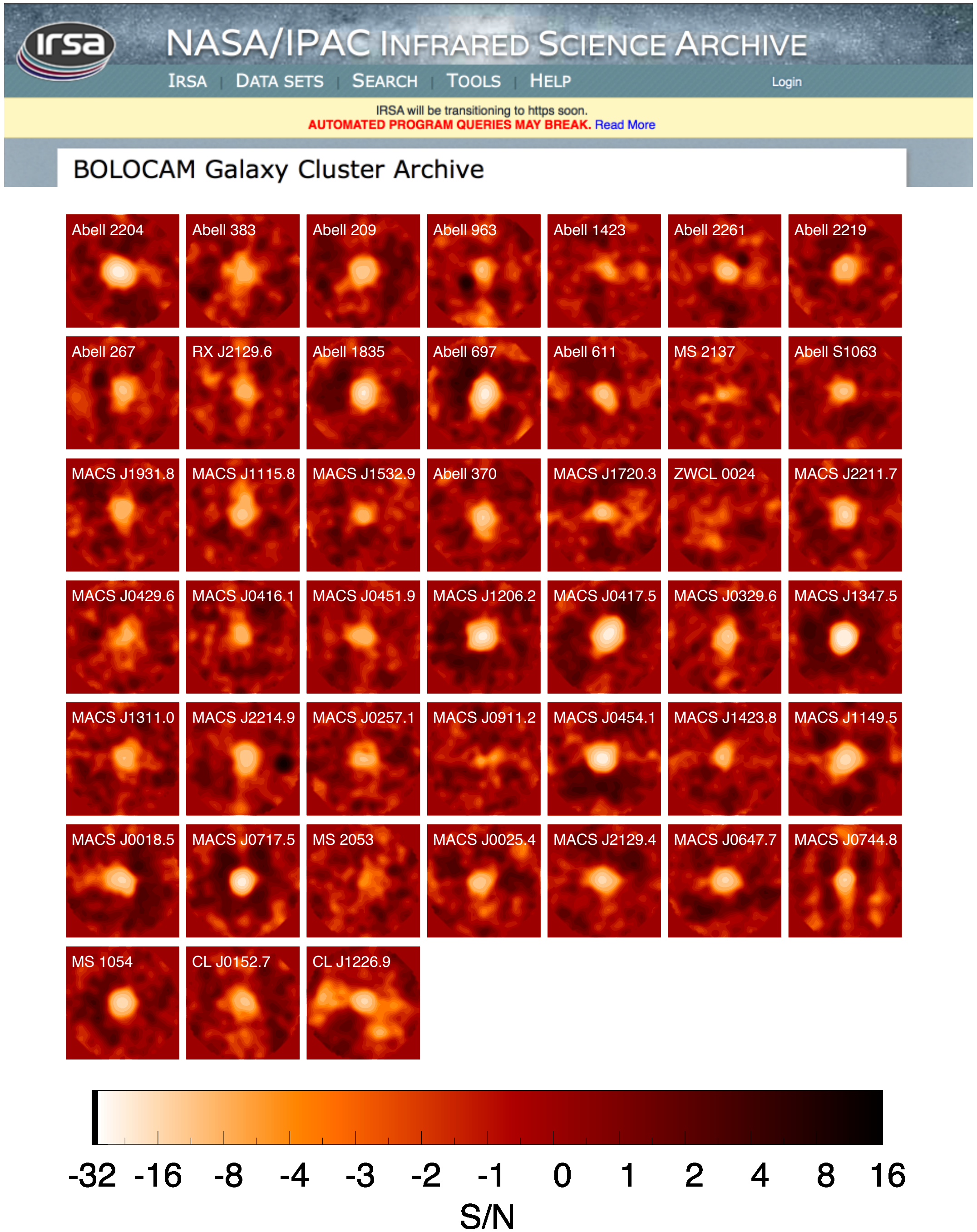




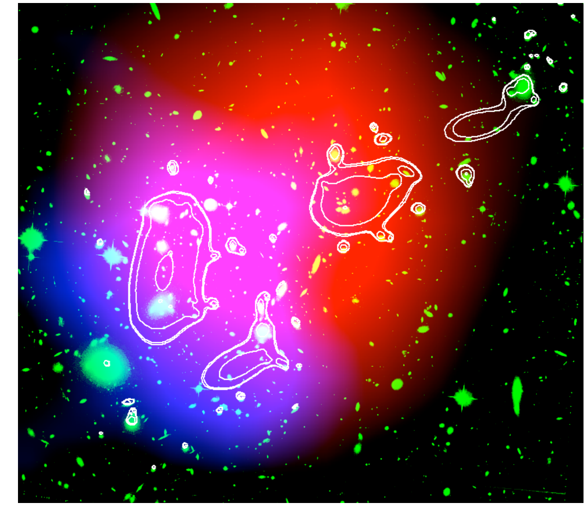


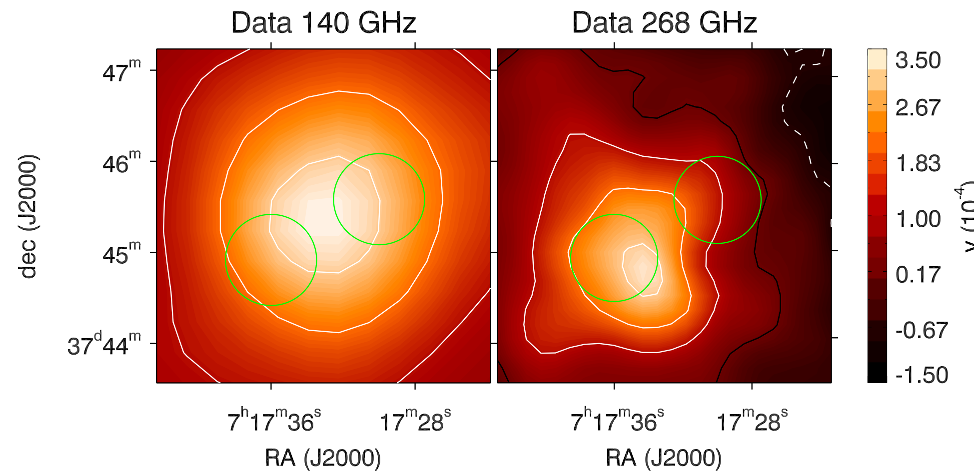


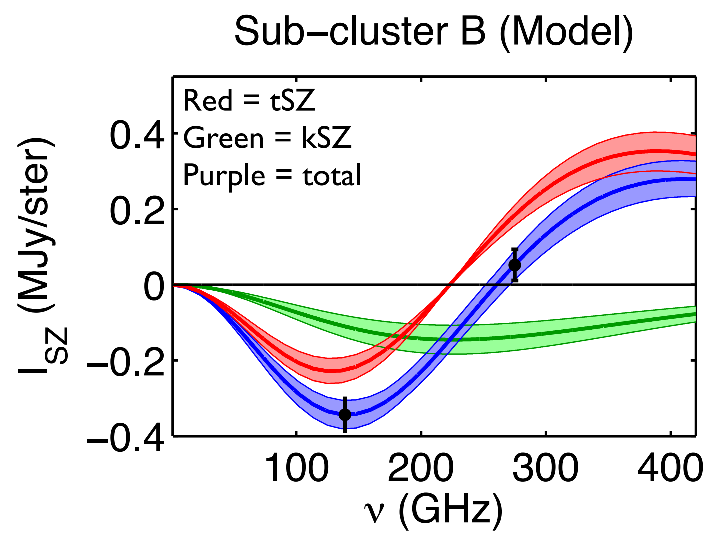
CSO History: Clusters



Detection of a 3000 km/s sub-cluster in MACSJ0717.5





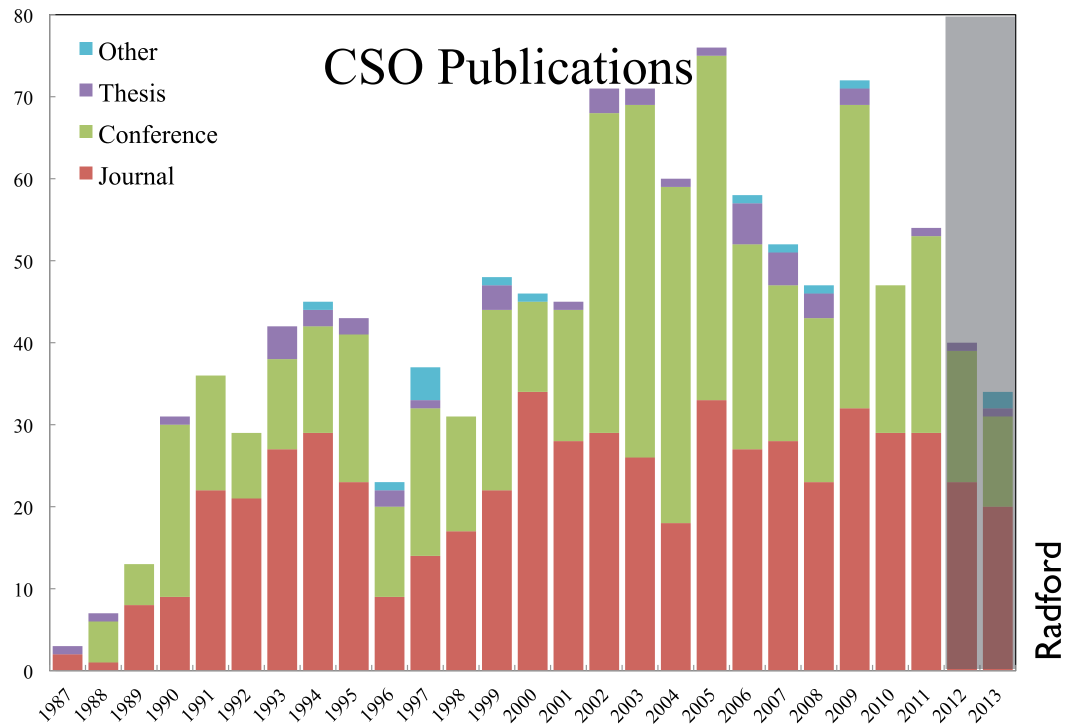


CSO History

2010s: Continued new instrumentation development

- Kinetic Inductance Detectors
  - Highly multiplexable superconducting detector technology invented at Caltech/JPL ~ 2000
  - Provides path to large CCD-like arrays of submm detectors
- Superconducting Microstripline
  - Enables "RF-style" circuitry at submm/mm wavelengths
    - Phased-array antennas covering wide bandwidths
    - Bandpass filters and filterbanks
- MUSIC
  - 4-band (850 μm - 2 mm) → 6-band (750 μm - 3 mm) imaging camera covering 14' FoV using phased-array antennas and bandpass filters
  - Imaging of dusty galaxies, clusters and galaxies in Sunyaev-Zeldovich effects, nearby star formation
- MAKO
  - Technology development toward 350 μm kilo pixel arrays using direct absorption KIDs
- SuperSpec
  - "Spectrometer-on-a-chip" using superconducting filter banks and KIDs, 100-500 GHz

Observatory, Interrupted



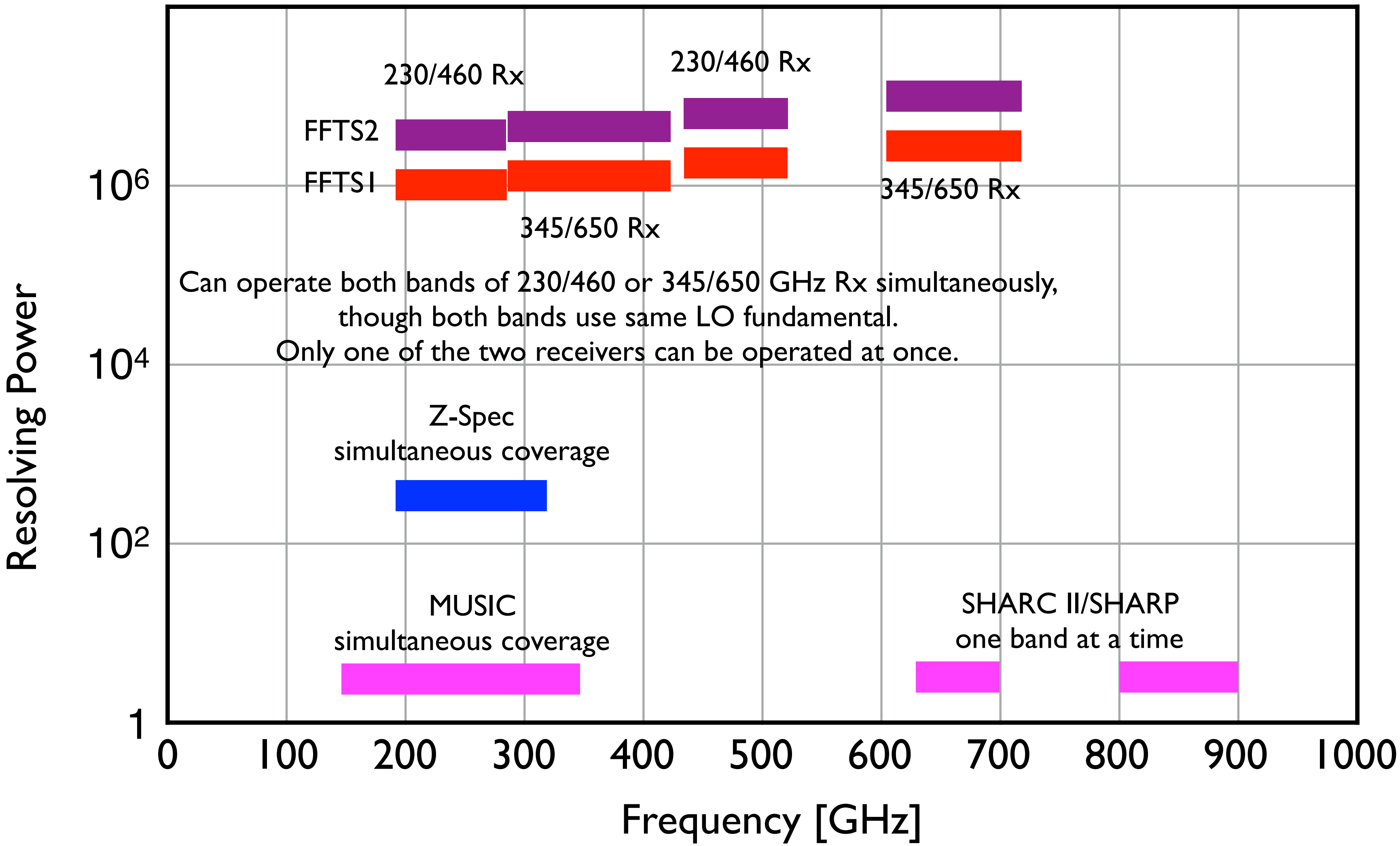
- ca. 2010: A vibrant observatory
  - Sustained scientific productivity
  - Multiple new instruments in dev't
  - Preparing handoff to CCAT
- An unfortunate series of events
  - 2009: Decommissioning announcement: Maunakea site not viable past 2016
  - 2011: NSF operating proposal declined
  - 2013: End of University Radio Observatory program
  - 2014: CCAT MSIP declined, consortium splinters
  - 2015: CSO suspends operations
- Strong motivation to find a path
  - In the midst of developing new scientific capabilities with new instruments
  - Telescope a unique resource: only 11 μm rms (850 GHz-capable), 10-m telescope
    - No concrete path to US access to such single-dish capability
  - Technology also reduced operating expenses
    - Full remote observing 2013 onward

The Leighton Chajnantor Telescope

LCT Motivation

- Most important: **Technology continues to move quickly**
  - SIS mixer bandwidth can be fully used w/wider-bandwidth IF amps and digital spectrometers
  - multiband imaging arrays, focal-plane-array spectrometers multiply effective time
  - 350 μm FoV can now be filled; would exceed SCUBA-2 450 μm capability
  - superconducting parametric amplifier: quantum-limited detection into the THz?
- Chile is a better millimeter and submillimeter site: ~1.5-2x better opacity on average
  - λ = 350 μm more regularly, less sky loading at λ = 850 μm, better sky noise for $\lambda \gtrsim$ 1 mm
- Leighton Telescope remains highest surface accuracy US-accessible 10-m aperture
  - 11 μm rms surface yields effective area equivalent to APEX 12-m (17 μm rms (→10 μm))
  - **CSO in process of being decommissioned: telescope could be lost forever**
- Telescope drives can be upgraded for fast scanning (~deg/sec) to freeze sky noise
  - Not conceived of at time of construction
- Field-of-view
  - FoV expanded by 3-4x in area with last mm-wave camera
  - Expanded 350 μm FoV never utilized (7' FoV, 30x current 350 μm camera FoV)
- 1000-hr programs are disfavored on 100% user facilities
  - [CII] tomography, deep cluster integrations, 350 μm DSFG surveys, etc.
- Complements ALMA: preparatory data, zero-spacing fluxes, integral quantities

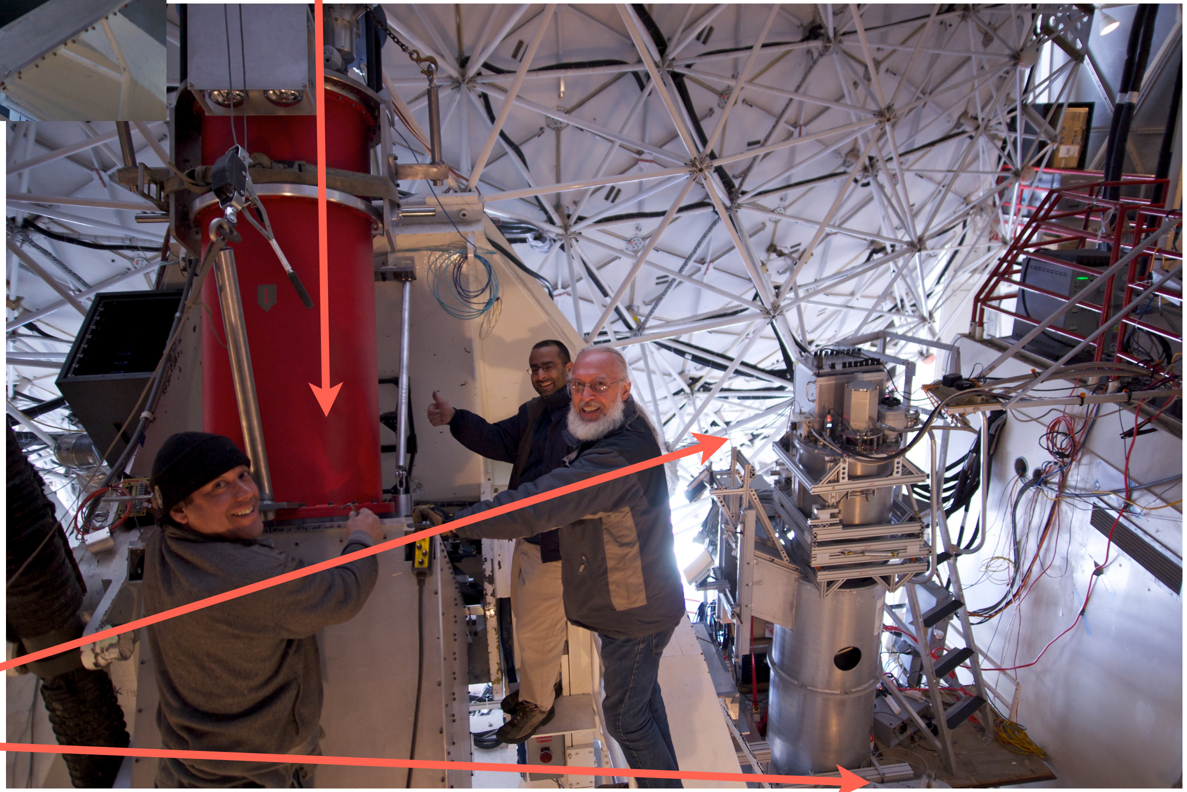
Instrumentation Suite: Recent Past



Instrumentation Suite: Recent Past

Broad instrument suite available at one time
Remote operation and instrument switching

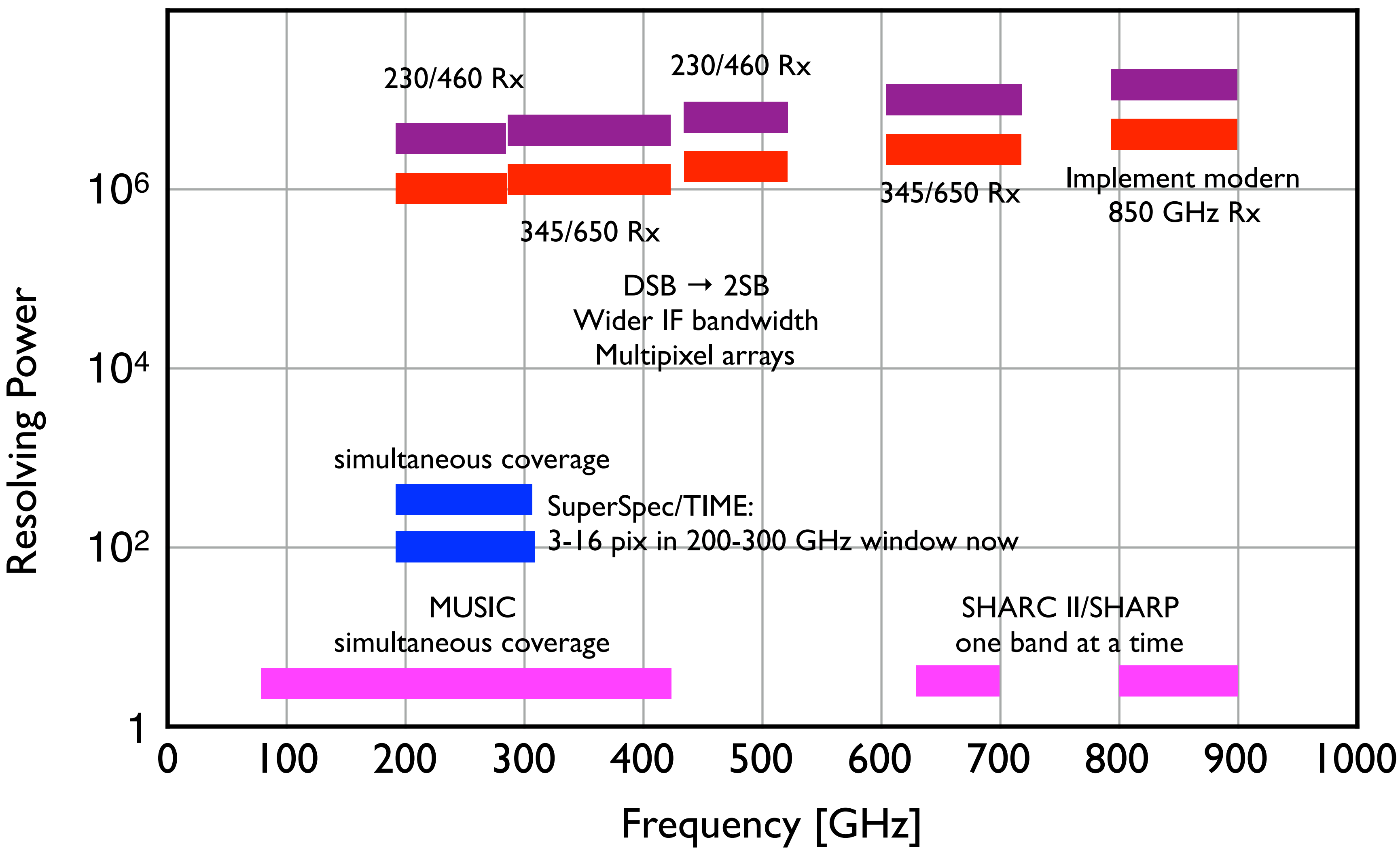
Alidade: Cassegrain Focus
- MUSIC
- Future wide-FoV
- Special tests (surface measurement, FTS, etc.)



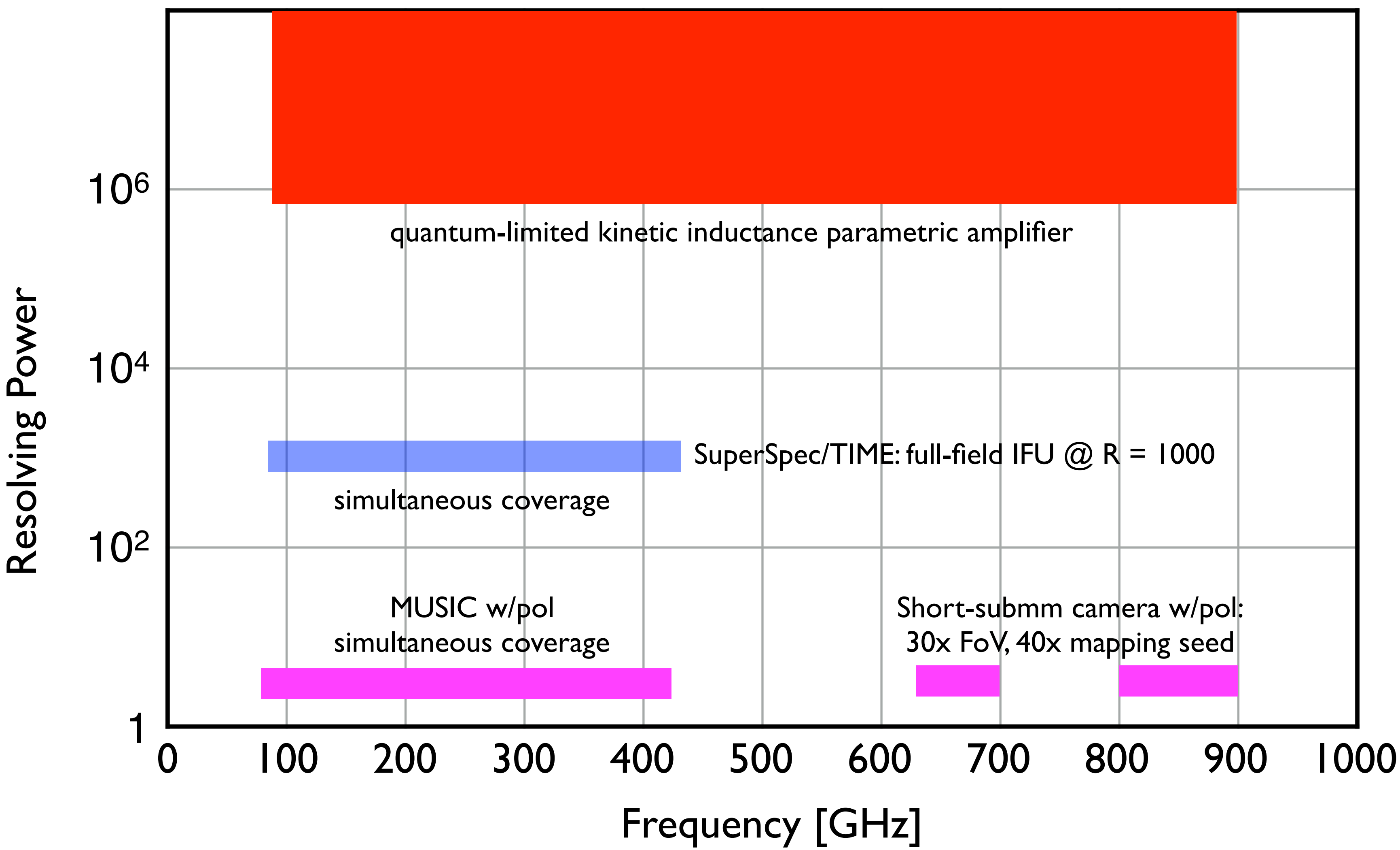
Sidecab (left Nasmyth):
- 230/460 dual color Rx
- 345/650 dual color Rx

Right Nasmyth:
- SHARC-II/SHARP
- Z-Spec resides adjacent

Instrumentation Suite: Near-Term



Instrumentation Suite: Long-Term



LCT Site: Excellent for Submm/mm Observations

Opacity

- 1.5x better at 350 μm: 350 μm band usable more of the time with better sensitivity
- 225 GHz opacity ~2x better on average

Sky noise

- Sky noise rms scales linearly with opacity/PWV
- More critical for wide-field mapping at mm wavelengths

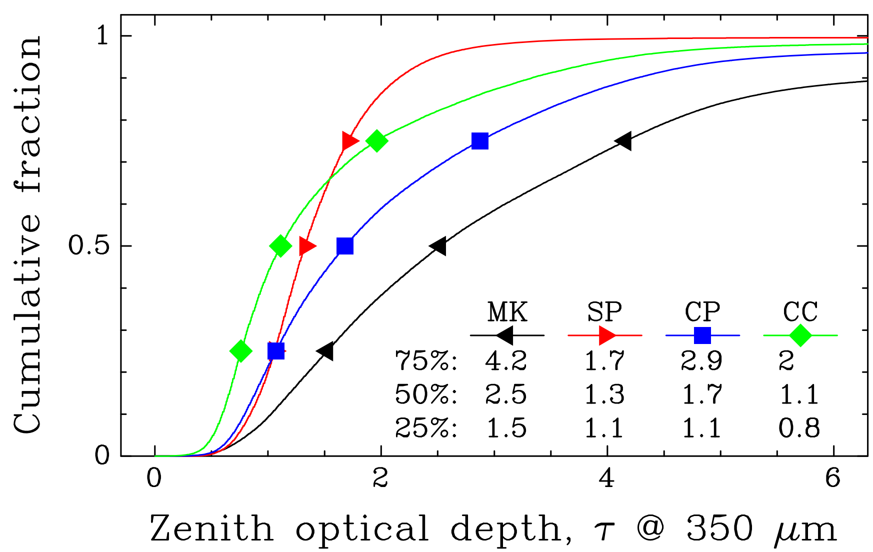
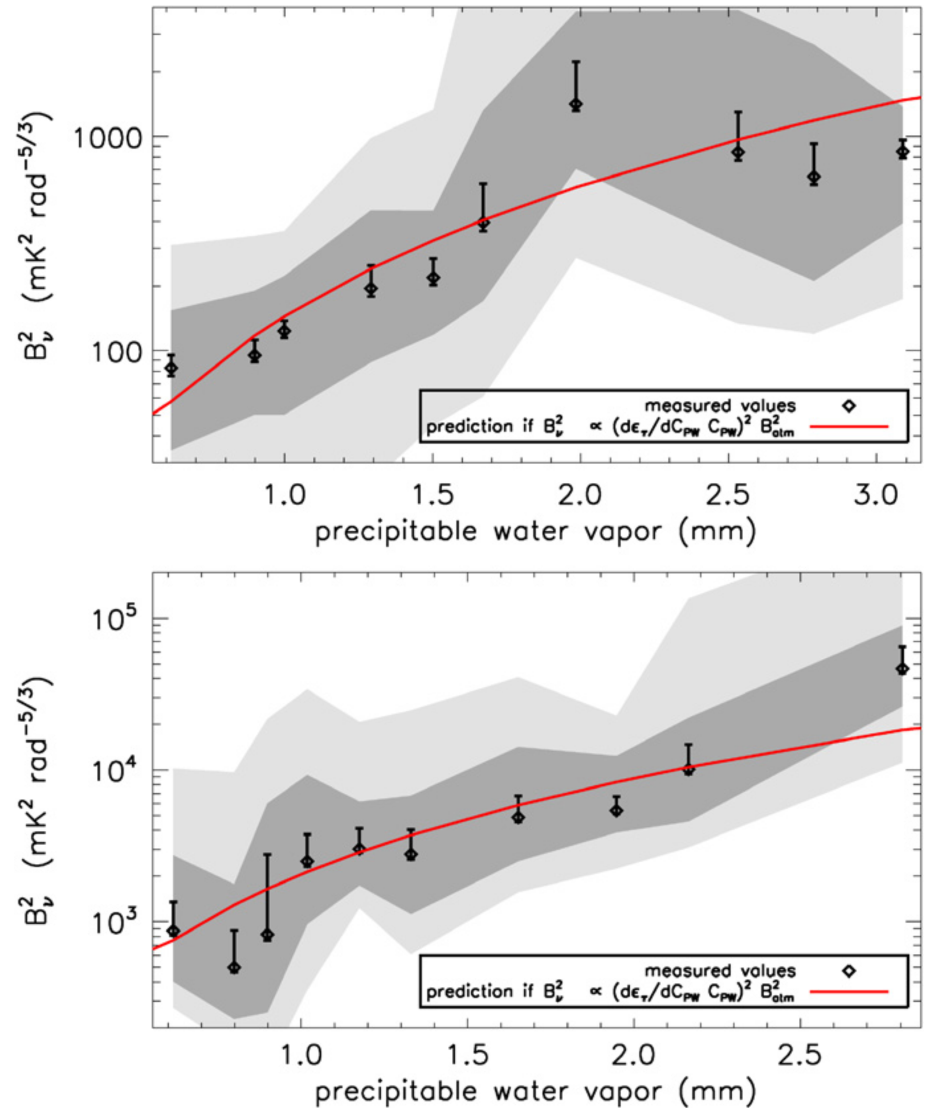


Figure 5. Cumulative distributions of broad band 350 μm zenith optical depths measured on Maunakea (MK), at the South Pole (SP), on the Chajnantor plateau (CP), and on Cerro Chajnantor (CC).

Radford and Peterson (2016)



Sayers et al (2010)

LCT Enablers: Telescope

Leighton Telescope is eminently transportable

- Limited surface retuning if primary moved in one piece
- 50 μm rms for OVRO moves
- APA move demonstrates prospect of move of intact primary
- Full move plan dev'd by RSS

APA move to Kitt Peak

Scenes from the move of the OVRO Leighton Telescopes to CARMA site

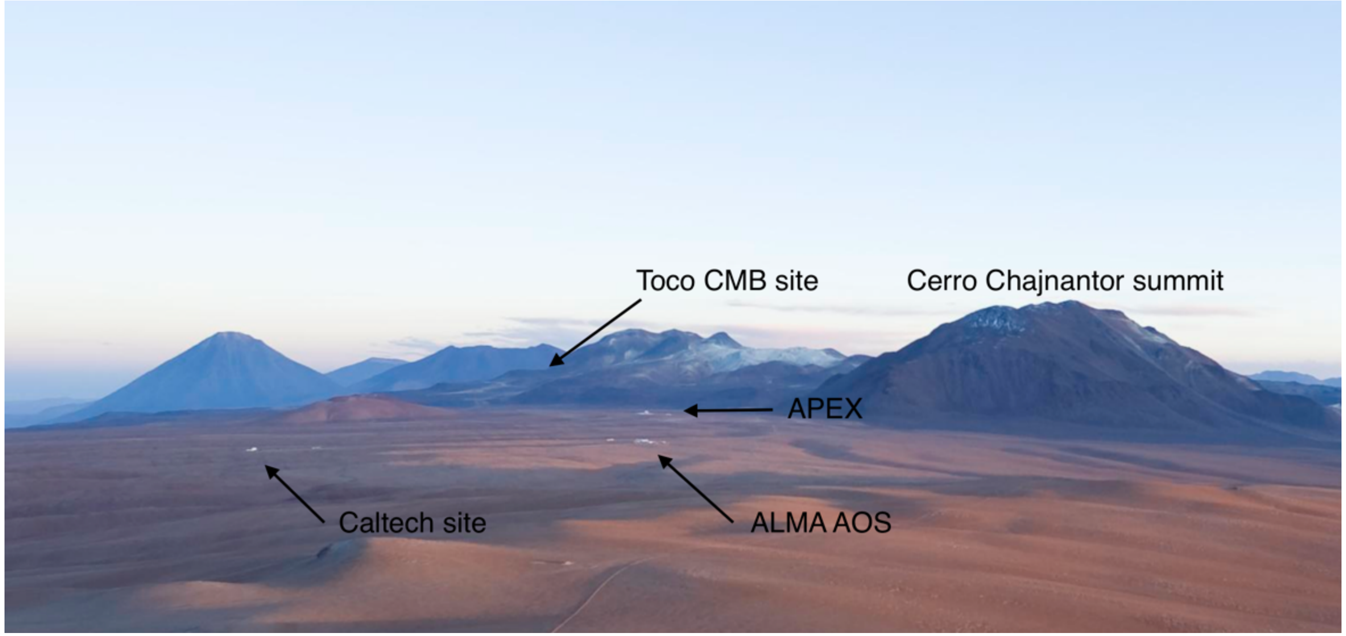


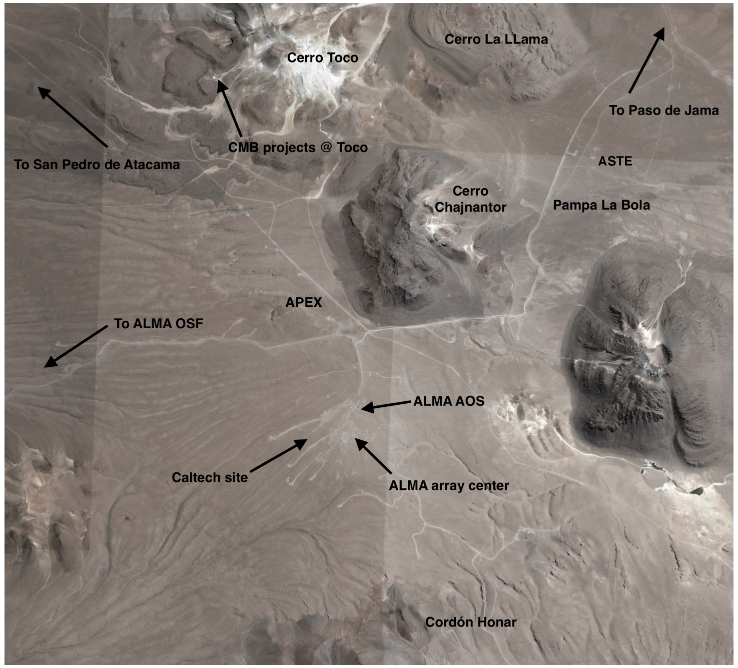


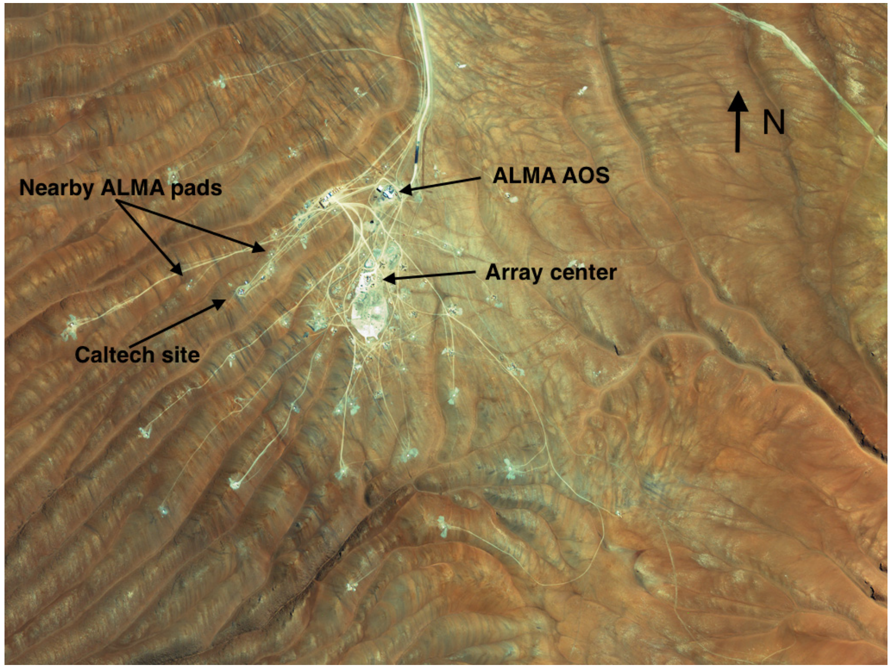

LCT Enablers: Site

Caltech est'd site
for CBI and QUIET

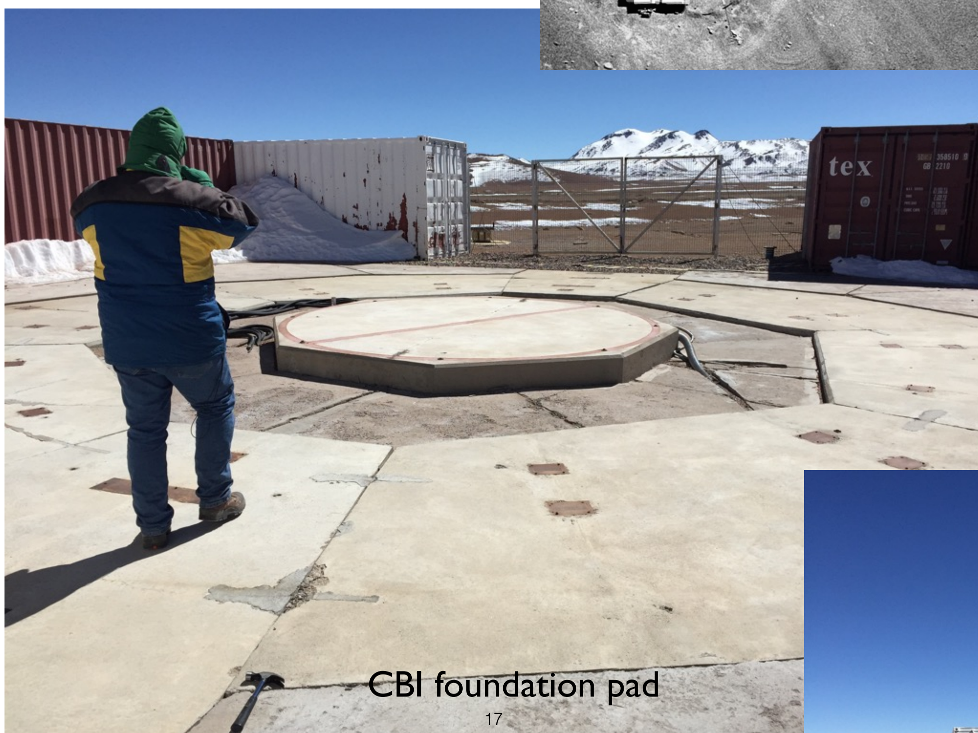
- Site allows expansion to meet LCT needs
- Inside ALMA: excellent physical access, proximity to utilities, safety





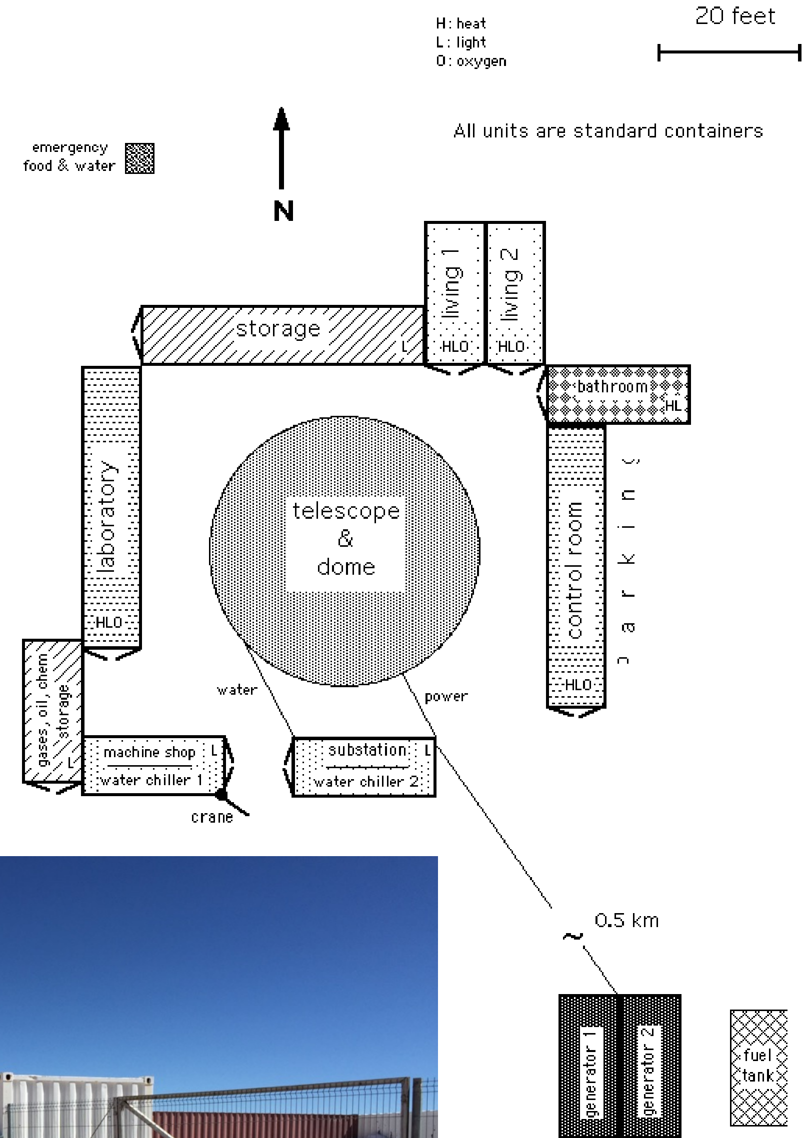


LCT Enablers: Site

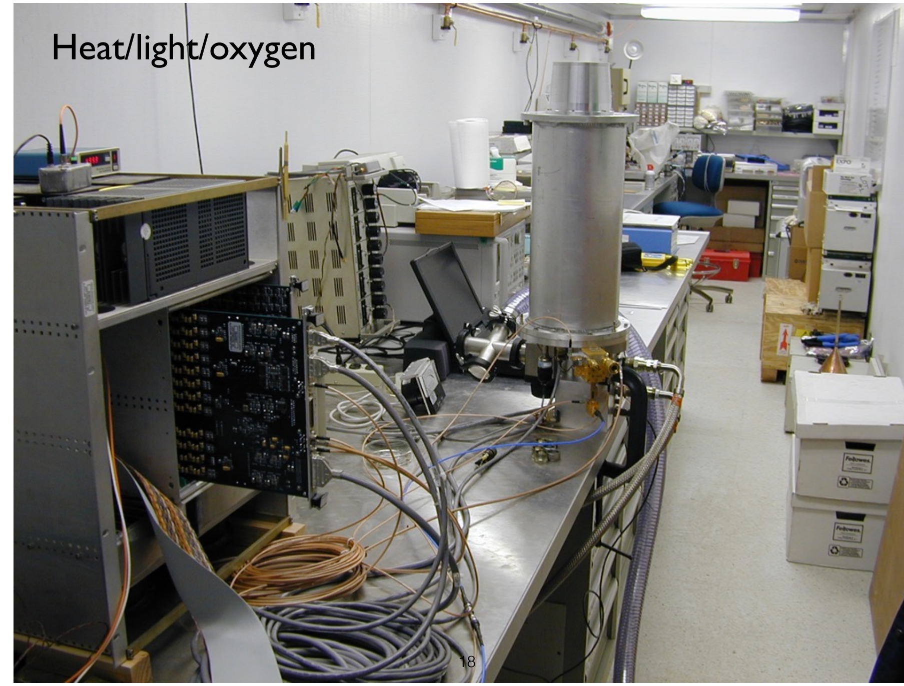


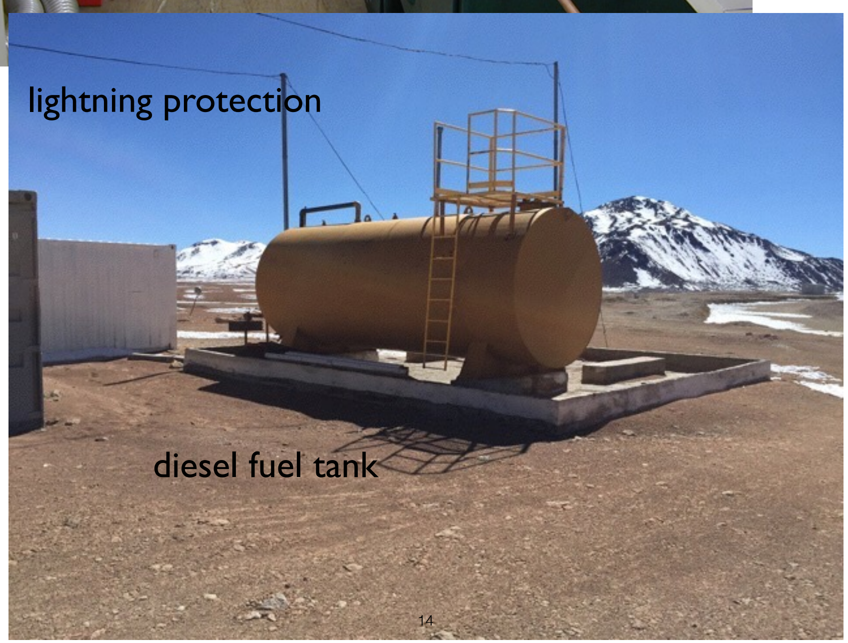
CBI foundation pad

entrance at SE corner



LCT Enablers: Site





LCT Science

Unique programs address compelling science questions
Possible only because of site and instrumentation
Executable only because of commitment
to ≥ 50% of time for 1000-hr-scale programs
New: many not conceived until post 2010
Other programs not possible in old operating model

LCT Planned Studies of Cosmic Baryonic Complexity Address 10 out of 19 Astro2010 Science Frontier Principle Questions (PQ) and 2 out of 5 Discovery Areas (DA)	
PQ1	What were the first objects to light up the universe and when did they do it?
PQ2	How do cosmic structures form and evolve?
PQ3	What are the connections between dark and luminous matter?
PQ4	What is the fossil record of galaxy evolution from the first stars to the present?
PQ5	How do stars and black holes form?
PQ6	How do circumstellar disks evolve and form planetary systems?
PQ7	How do baryons cycle in and out of galaxies and what do they do while they are there?
PQ8	What are the flows of matter and energy in the circumgalactic medium?
PQ9	What controls the mass-energy-chemical cycles within galaxies?
PQ10	How do black holes work and influence their surroundings (here, galaxy assembly)?
DA1	Time-Domain Astronomy
DA2	The Epoch of Reionization (EoR; 0.1-1 Gyr)

Science Target/ Astro2010 PQ/DA	Desired Science Measurement	Enabling Capabilities			Req'd Survey Parameters
		Receivers	Telescope/Optics	Site	
EoR: Constrain total [CII] emission from reionizing galaxies to test reionizing photon budget (**PQ1, PQ2, PQ3, PQ4, PQ8; DA2**)	**[CII] power spectrum SNR:** >10 (5) for z=5.3-6.2 (z=6.2-8.5) **SFR history SNR:** > 5 (5) for z=5.3-6.2 (z=6.2-8.5) **H_2 history SNR:** > 5 in each of 5 bins z=0.5-2	**TIME** provides multi-pixel high-sensitivity, low-resolution spectroscopy • R ~ 100 for 200-300 GHz • NEFD ~100 mJy√s • 16 pixels • 1 beam x 14′ FoV	0.5 deg/s² acceleration FoV ~ 14′ accommodates K-mirror image rotator > 93% telescope+relay optics eff. (rough. x refl.)	75% $T_{225} < 0.1$: low sky noise	1000 hr survey of 2 fields, each 1 beam x 1.3°
IGM/ICM/CGM: Test for non-therm. pressure (~50% @ R_{200m}) and non-therm. velocities ~500 km/s at R_{500c} in $M_{500c} = 10^{15}$ $M_\odot$ clusters (**PQ2, PQ3, PQ7, PQ8, PQ10**)	**tSZ:** SNR ~ 200 measures non-thermal pressure fraction to ~1% precision (absolute) **kSZ:** σ_v = 100 km/s per sq. amin. at r < R_{500c} gives SNR = 5 per sq. amin. for 500 km/s non-thermal velocities	**MUSIC** provides wide-FoV imaging simultaneously in multiple bands to measure tSZ, kSZ, and contaminants: • 6 bands 90-405 GHz • NEFD ~ 15, 20, 25, 35, 60, 120 mJy√s at 90, 150, 220, 290, 350, 405 GHz • 14′ FoV	0.5 deg/s² acceleration FoV ~ 14′ Lissajous scanning > 95/93/90% at 150/290/350 GHz telescope+relay optics efficiency (rough. x refl. x feedleg blockage)	75% $T_{225} < 0.1$: low sky noise, high atm. transm. in 350/405 GHz bands	1200 hr survey of 20 clusters
Energetic transients in dense CSM: Detect transients with high peak freq. (>100 GHz) at 5-10/yr (search radius 150 Mpc) (**DA1**)	1 mJy rms in multiple bands near 300 GHz to isolate emission peak out to r = 150 Mpc 2 mJy rms @ 850 GHz flux to probe extent of sync spectrum for nearer/more luminous srces	**MUSIC** provides simultaneous multi-band photometry to isolate peak across >5:1 bandwidth **SHARC2** provides 850 GHz photometry • NEFD ~ 600 mJy√s at 850 GHz	**mm:** same acceleration, Lissajous scanning, and optics eff. **submm:** 11 μm rms surface	**mm:** same **submm:** 25% $T_{850} < 0.7$	Fast-rising O/IR transients: **MUSIC:** 20-min/night, grid in log(days) **SHARC2:** 5-hr integrations during plateau w/few day cadence, best 25% T_{850}
Galaxy transition from star-forming to quiescence (**PQ4, PQ7, PQ8, PQ10**)	**SFR:** 6 mJy rms @ 850 GHz → 20% SFR measurements **M_{dust}, β:** 1 mJy rms in 2-3 bands @ 300 GHz → 20% flux errors	**SHARC2** provides 850 GHz photometry **MUSIC** provides multi-band photometry over dust RJ tail (and may constrain free-free and sync too)	same	same	1000-hr survey of all ~500 visible WISE W1W2 dropouts, 1 hr/src each w/ **MUSIC** and **SHARC2**
Role of magnetic fields in star formation on scales between Planck and ALMA (**PQ5, PQ6**)	1% polarized dust emission @ 300, 850 GHz to get field orientation in various dust pops. Zeeman splitting in CN and SO for line-of-sight field strength	**MUSIC** provides polarimetry in multiple bands near 300 GHz **SHARP** provides 850 GHz polarimetry Future **100 GHz MMIC Focal Plane Array** will do Zeeman splitting	same + wide FoV	same	900-hr survey of 100 Planck sources; 3, 6 hrs/src each with **MUSIC** and **SHARC2**
Role of dust grain size dist'n in star (**PQ5**) and proto-planetary disk (**PQ6**) formation	Constrain dust β by measuring SED to 2, 4, 5 mJy rms at 220, 290, 350 GHz (10x precision of ATLASGAL, BGPS)	**MUSIC** provides measurements of dust SED on RJ tail in multiple bands near 300 GHz, separates free-free and sync; power law identifies grain size	same	same	500 hr survey of 500 sq. deg. of galactic plane

1200-1500 hrs/yr for surveys

4500 hrs survey time in 3-4 yrs

many programs would seed ALMA followup: new classes of targets

new surveys as new capabilities become available

vigorous instrumentation dev't and fast deployment a necessity

PI time:
ideal for ALMA preparatory data

LCT Roles

Shanghai Normal University

- Lead for Chinese involvement
- Oversight of CASSACA effort in Chile
  - New enclosure design/construction
  - Site infrastructure
- Interface to Chinese user community (via CASSACA/NAOC)

Universidad de Concepcion

- Lead for Chilean Involvement
- Operations lead
- Interface to Chilean user community

Caltech

- Technical heritage → technical leadership role during deconstr/move/recom phase
- Continued technology development primarily in bolometers and parametric amplifier
- Continued science leadership
  - esp. large surveys using new instrumentation

New Receiver Labs at ShNU/UdeC

- Refurbish/build SIS heterodyne receivers
  - 345/650 at ShNU, 230/460 at UdeC
- Involvement in future developments
  - array receivers, 850 GHz, param. amp.
  - joint with PMO
- Personnel
  - ShNU staff Dr. Duo Cao worked with CSO experts to test SIS Rx's 2018
  - UdeC ramping up expertise via visits to Caltech, ShNU

LCT Progress and Status

Late 2015/early 2016: Readhead midwifes collaboration to move CSO to CBI site in Chile

- Caltech (Golwala)
- Chinese Academy of Sciences South American Center for Astronomy (CASSACA; Zhong Wang, former OVRO postdoc),
- Universidad de Concepcion (Reeves, former CBI/QUIET engineer/postdoc)

2016

- Conceptual Design Report (CDR) written
- RSS contracted to estimate move cost: $1.4M + contingency

2017

- Shanghai Normal University brought in as Chinese university partner
- CDR results in "preliminary and provisional approval" from ALMA to use the CBI site pending approval of Foreign Ministry and CONICYT

2018

- PM Gary Parks engaged to develop full cost/schedule estimate
- Foreign Ministry approves LCT on basis of preexisting CBI approval
- ShNU receives ~50% of funds needed to undertake project, deemed "national project"
- Terms for CONICYT approval developed with CONICYT Astronomy director

2019

- Submit NSF MRI and MSRI proposals

LCT Funding Model and Community Participation Ideas

Planning/Project Development

- Caltech/CASSACA discretionary funds, ~$400k spent to date

Disassembly/Move/Recommissioning (DMR) Phase: ~$8M

- ShNU funds in hand ~50%
- In-kind manpower contribution from UdeC and CASSACA
- Caltech seeking NSF funds for 2nd half in exchange for survey data access

Operations Phase: ~$1M/yr

- CASSACA in-kind manpower
  - 2 techs, 1 engineer
- UdeC in-kind manpower
  - Technical Manager, 1 engineer, 1 programmer/IT, admin support, including hosting local operations office)
- ShNU cash contributions

Community involvement ideas:

- NSF MRI or MSRI funds are buy-in, provide access to survey data: $4M
- Tech demo nights in exchange for NSF ATI/NASA SAT funding
  - 10 nights for $100k/yr? Provides on-sky testing of PI instruments or of NASA mission pathfinders
- PI nights or survey participation in exchange for NSF operations funding
  - $300k-$400k/yr for 30-40 nights PI time or survey participation?
- PI instruments
  - Science access in exchange for serving instrument to user community?

Conclusions

CSO has long and accomplished history of opening submm windows, continuing cutting-edge instrumentation development

Decommissioning of CSO presents deadline for use of unmatched Leighton Telescope

LCT project planning is moving forward

- Developing full project plan, budget, schedule
- Working on completing funding, developing opportunities for community participation